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Sent: Friday, August 15, 2008 2:43 PM
To: zzMSHA-Standards - Comments to Fed Reg Group
Cc: MSHA-Comments@dol.gov
Subject: RIN 1219-AB60

Veyance Technologies, Inc. 's comments on the RFI and Appendix A to our comments are attached.
Appendixes B and C will be sent in an immediately following email.

Thank You and Have a Good Day !!!!!

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AB60-COMM-2



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August 15, 2008

Mine Safety and Health Administration
Office of Standards, Regulations and Variances
1100 Wilson Boulevard
Room 2350
Arlington, VA 22209-3939

RE: **RIN 1219-AB60**

Dear MSHA:

Veyance Technologies, Inc. (Veyance) very much appreciates the Mine Safety and Health Administration (MSHA) initiating this proceeding on Conveyor Belt Combustion Toxicity and Smoke Density. The opening of this conveyor belt fire safety proceeding, alongside the agency's flame-resistance rulemaking (RIN 1219-AB59), demonstrates the ongoing personal and organizational dedication by MSHA professionals to underground mine safety.

I. Veyance's Commitment

Veyance is committed to **comprehensive** conveyor belt safety. Comprehensive safety in underground coal mines means that strong, mandatory standards are set for: 1) flame-resistance; and 2) smoke density. As part of our commitment to comprehensive conveyor belt safety, Veyance strongly urges MSHA to concurrently mandate flame-resistance and smoke density standards for all conveyor belts used in underground coal mines. Veyance also recommends that MSHA adopt a drum friction test.

II. MSHA's Opportunity

By initiating this proceeding on smoke density and combustion toxicity in conjunction with the flame-resistance rulemaking, MSHA has the opportunity to create a comprehensive conveyor belt fire safety standard. It is only through a comprehensive approach to belt safety that MSHA can fulfill its mission of providing appropriate protection from belt fire hazards to underground miners. As Veyance will document below, a partial approach to conveyor belt fire safety which delays smoke density standards would not provide adequate protection to miners and could even potentially increase certain hazards.

III. Veyance's Approach to Setting Smoke Density Standards

Veyance's extensive research and development work on limiting smoke density and toxicity from overheated conveyor belts is based on:

1. Consensus Standards Testing Methods. All of the tests described below, measure smoke density and the components of smoke toxicity use laboratory-scale, voluntary technical standards developed by recognized standards developing organizations such as the ASTM International (formerly the American Society for Testing and Materials.) All of the standards used by Veyance are already used by federal regulatory agencies for fire safety. Copies of each testing standard are attached as appendixes to these comments.
2. Open Sourcing/Modern Technology. All of the flame retardant compounds Veyance has used in developing low smoke conveyor belts that meet the proposed Belt Evaluation Laboratory Test (BELT) are off-the-shelf compounds available from third-party chemical suppliers. No Veyance-proprietary or Veyance-exclusive compounds were used. Instead, Veyance is taking advantage of "halogen free" flame retardants that are being adopted in various industries around the world.

As Veyance will explain in Section XI, companies and countries are phasing out halogenated flame retardants in various industries because modern alternatives: 1) produce less smoke; 2) produce less toxic smoke; and 3) are more environmentally friendly.

While Veyance is not recommending the use of any specific technology, it is clear that MSHA should use revision of the underground conveyor flammability standards as an opportunity to set performance standards that take advantage of the modern, cost-effective technologies available to all manufacturers.

IV. Cost

In its Request for Information (RFI), MSHA asked about the "difference in cost and performance between conventional materials and these new [reduced smoke and toxic combustion product] materials." There is no difference in cost or performance (durability, abrasion resistance, ability to pass a drum friction test, etc.) Low-smoke conveyor belting meeting the BELT is no more expensive than high-smoke belt meeting the same flame resistance standard. Thus, **use of low-smoke BELT-compliant conveyor belts provides additional safety at no additional cost.**

In its flame-resistance rulemaking, MSHA explained that regulatory agencies are required to "assess both the costs and benefits of regulations." It is important that MSHA's cost-benefit analysis recognize that by combining low-smoke and higher flame-resistance requirements, MSHA can achieve significantly higher levels of underground safety without additional cost, a win-win-win situation for miners, mine owners and all other safety stakeholders.

V. Why Low-Smoke Conveyor Belt is Essential to Underground Coal Mine Safety

1. Smoke Causes Multiple Impediments to Mine Escape. Federal research performed by the National Institute of Occupational Safety and Health (NIOSH), based on both controlled experiments and interviews with miners who escaped from underground fires, highlight and document the multiple dangers of smoke and, in specific, the different ways in which smoke hinders the ability of miners to find safety.

In a controlled experiment measuring “both physiological and psychological response to smoke produced from smoldering wood” in which subjects were “told to thrust the stylus into the holes in a specific order, but trying not to touch the sides of the holes... [researcher] Jin noted that as the smoke density increased, fear of the smoke coupled with irritations of the eyes and throat impeded individuals' ability to concentrate on the task of operating the steadiness tester.”¹

Based on interviews with mine fire survivors, NIOSH noted that “individuals who escaped the mine fires reported visibility distances that were often far below those calculated from Jin's results.”² A miner is quoted as saying, “The [stopping] was probably on the other side of these props, but I couldn't see it. I couldn't even see the door, that's how thick it was. I put my hands out...and I couldn't see the end of my fingers.”³

Another miner recounted how “I walked up there to the overcast and I stepped right into it. And it was like a black wall. It was like burning 50 tires and trying to walk through it...and I said, ‘We can't go that way.’ So we walked out and there was some—I know there was doors in those overcasts. I said, ‘The intake's here someplace. All we've got to do is find it.’ And you'd open up the door and it'd just billow out; and you'd open another door and it would billow out...we opened up [one] door, it looked like it was a black river running by. That's how thick it was.”

NIOSH explained that at “Brownfield Mine, the smoke was so heavy that a foreman actually walked into the belt structure while attempting to make his way to the other side of 6 West mains to check for fresh air in the No. 7 intake.”⁴

¹ C. Vaught, Ph.D., M. J. Brnich, Jr., L. G. Mallett, Ph.D., H. P. Cole, Ed.D., W. J. Wiehagen, R. S. Conti, K. M. Kowalski, Ph.D., and C. D. Litton, “Behavioral and Organizational Dimensions of Underground Mine Fires,” US Department of Health and Human Services, National Institute for Occupational Safety and Health Pittsburgh Research Laboratory, May 2000, p. 118. [Emphasis added.]

² Ibid., p. 122.

³ Ibid. pp. 121-122.

⁴ Ibid., p. 122.

The NIOSH study documents that the psychological effects of heavy smoke harmed the ability of miners to perform basic survival tasks, such as donning SCSRs. The study quotes a wireman who had been in the 7 Butt section of Cokedale Mine as saying, “We were in the jeep, and we hit smoke. I got all scared you know, all, what the hell we going to do, you know, all this smoke...And I was on the jeep, and [the boss] said, ‘Get your SCSRs on.’ And I...opened mine up and I was like shakin' like a leaf, couldn't get the damn thing open. And [the boss]...said, ‘Here, pop this, stick this in your mouth...’ I mean, I couldn't get the damned thing, I was so damned scared I didn't know what else, I didn't know what the hell to do, you know.”⁵

NIOSH also explained that “Apprehension about the smoke caused one of the shuttle car operators at Adelaide Mine to experience difficulty breathing, even though he was wearing an SCSR and was protected from the smoke.” The miner recounted that “We went into that smoke and I couldn't breathe and was gagging on that self-rescuer. I couldn't breathe any at all...I couldn't go in [that smoke]. I guess it may be psychological or something about being in that smoke or something. I couldn't breathe at all. In [the smoke] I was gagging but as soon as I would come out of there, it seemed like I was breathing better, a little bit better.”⁶

The result of even a single miner being overwhelmed by smoke can endanger many others as they attempt to rescue their co-worker. “Because of his experience, the shuttle car operator chose not to follow his buddies into the heavy smoke at the overcast. Instead, recognizing where he was, he decided to follow another route that led him across 2 Northwest Mains and down the right-side return escapeway to a point outby the fire. This decision is significant because several of the miner's buddies, believing him to be lost, risked their lives by going back to the overcast to look for him after everyone had reached safety.”⁷

The critical hazards to miners from thick smoke goes beyond visual loss, respiratory irritation, and anxiety effects. NIOSH states that “While some miners became afraid in the smoke, others became confused and disoriented. This inhibited some miners' ability to think clearly and respond functionally to the situation. The Federal mine inspector, who escaped from 4 South at Brownfield Mine, had conducted numerous inspections in the sections off 6 West Mains and was moderately familiar with the layout of that portion of the mine. Nevertheless, he reported becoming disoriented and confused in the heavy smoke, especially toward the end of his ordeal as he made his way from the belt entry to the track.”⁸

⁵ Ibid, pp. 124-125.

⁶ Ibid, p. 125.

⁷ Ibid.

⁸ Ibid.

NIOSH summarized that “It is evident from these accounts that miners experienced great emotional trauma while escaping through the smoke-filled passageways. In some cases, miners' ability to concentrate, make informed choices, and take appropriate actions during their escape was severely hampered by the need to deal with emotional effects of the smoke.”⁹

In addition to the effects of visually obstructive smoke, NIOSH recognized the other escape difficulties resulting from the irritant compounds in the smoke, a crucial factor in the this proceeding and the flame-resistance rulemaking since, as we will document below, unless controlled, the concentration of smoke irritants such as HCl will increase as more flame retardants are used to meet the proposed BELT standard. As NIOSH noted, “Besides having to cope with the psychological effects of smoke in their escape environment, many miners had to contend with physiological elements as well. Smoke clouds carry CO as well as sensory irritants, both of which are byproducts of combustion.”¹⁰

It is crucial to note that NIOSH has recognized the potential hazards from chlorinated flame retardants commonly used to increase flame-resistance. As NIOSH stated, “Depending on the material burning, other toxic and irritating elements can be produced. For conveyor belts, in particular, the generation of HCl vapor due to chlorine in the belt, as either a component of the base polymer or as an additive to make the belt more flame-resistant, is an example of such an irritant and also represents a potential toxic hazard in addition to the CO produced.”¹¹

It should be noted that a Canadian state safety agency recognized the potentially lethal danger in mine fires of gases other than CO. The Saskatchewan Labour Occupational Safety and Health Division explained that “About 10 percent of all fire deaths are unexplained by carbon monoxide poisoning or other clear causes. They include deaths with signs and symptoms of respiratory tract irritants. Such irritants prevent proper breathing (i.e. choking, suffocation) and impede escape, thus increasing exposure to asphyxiants such as carbon monoxide and hydrogen cyanide.”¹²

While recognizing the potential dangers from toxins, NIOSH also focuses on smoke as the most severe hazard to miners. Specifically, “the presence of smoke poses a more

⁹ Ibid., p. 127.

¹⁰ Ibid.

¹¹ Ibid., p. 130. [Emphasis added.]

¹² “Saskatchewan Mine Emergency Response Program: Mine Rescue Manual,” February 2001, p. 68.

severe impediment to survivability and eventual escape from fire than the toxicity of the gases produced.”

The NIOSH research also examined the physiological problems experienced by miners in smoke including those miners with functioning SCSRs, “It is understandable why miners experienced emotional instability during their escape through smoke from these fires. However, one might question why more than one-third experienced physiological problems since miners would have been offered respiratory protection from either their SCSR or FSR and eye protection from the goggles contained in their SCSR. These problems are easily explained: besides removing the mouthpiece to breathe, as mentioned earlier, nearly 48% of the miners who escaped also took the mouthpiece out in smoke to talk. Subsequently, miners inhaled smoke and various contaminants which caused them to experience breathing discomfort. The interviews also revealed that few miners wore the goggles supplied with their SCSR to protect their eyes. Many of the miners said that the goggles fogged quickly and hampered their vision. As a result, more than 63% of the escaping miners said they did not wear the goggles for that reason.”¹³ Thus, while functioning SCSRs and training in their proper use are essential elements of underground safety, they are not a substitute for low-smoke conveyor belting.

The NIOSH study also noted that miners were confronted with heavy smoke where it was not expected. For example, a miner explained that “We started down the belt because we figured the belt should have been neutral, really, but by the time we got there, the smoke was already on the belt line...we still can't figure out how the smoke got on the belt. Nobody—our boss can't figure out how the smoke got on the belt line. We should have been able to go down and get out the belt.”¹⁴

A mine inspector who escaped from 4 South at Brownfield Mine hypothesized but could not be sure why the belt entry became smoke-filled, “To this day we really didn't conclusively come up with an answer why that belt got contaminated. We checked the [stoppings]. I understand [stoppings] do leak somewhat but not to go from no smoke to thick heavy smoke in a matter of minutes. [Stoppings] don't leak that much. Someone left the doors open into that belt, also. I believe it.”¹⁵

2. Smoldering Belts. All conveyor belts, irrespective of materials used, will give off smoke and toxic gasses when they are overheated, even if there is no fire. Veyance test results demonstrate that smoldering belts can give off thick, black smoke (detailed below) without any flame. The Bureau of Mines recognized years ago, with respect to

¹³ “Behavioral and Organizational Dimensions of Underground Mine Fires,” p. 132.

¹⁴ Ibid., p. 135.

¹⁵ Ibid.

conveyor belts and other mine materials, that the “principal hazards encountered in smoldering combustion involve toxic gas and smoke production.”¹⁶

3. Flame-Resistant Does NOT Mean Fire-Proof. The proposed BELT standard would increase the minimum level of flame resistance for conveyor belts but does not mean that the belt would be fire-proof – no belt or other material can ever be considered as fire proof. The BELT protocol calls for gas jets to be applied to one end of a five foot sample of conveyor belting. The sample passes if any portion of the sample remains undamaged. Thus, fire can consume almost the entire length of test sample and the belt still passes the test.

Since federal safety officials have extensively documented the multi-level hazards smoke presents to miners attempting to escape, and as detailed below, the proposed BELT standard has the potential to lead to even thicker smoke, *how could MSHA not speedily implement low-smoke density belt standards concurrent with the flame resistance rule?*

VI. The Technical Study Panel Expressed Concerns About Smoke

Although the charter for the Technical Study Panel (TSP) created by the MINER Act did not specify discussion of smoke and toxic fume issues, panel members expressed serious concerns about smoke toxicity. For example,

“DR. WEEKS: ... Just by way of clarification, but toxicity you were talking about the toxicity of smoke from belt fires?

DR. CALIZAYA: Yes.

DR. WEEKS: No. We didn't address that.

DR. CALIZAYA: Well, regarding this point I think at least to me based on the hearings we had before we should address that point of toxicity.

We know that it's the fumes that will cause any accidental death that we may have in mines. If we have toxic fumes then definitely we are allowing that to take place.”¹⁷

DR. WEEKS: Well, no other word changes, but, Jerry, did you have some more to say about the toxicity of smoke? I don't want to let this issue just get shoved under the rug.

DR. TIEN: Yes, but obviously we are.”

¹⁶ U.S. Department of Interior, Bureau of Mines, Information Circular 9272, “Summary of Combustion Products From Mine Materials: Their Relevance to Mine Fire Detection,” p. 7.

¹⁷ Transcript of Proceedings, Technical Study Panel meeting, September 17, 2007, p. 40, pp. 47-48.

VII. Congress Calls for Smoke Safety Regulations

In the S-MINER Act (H.R. 2768) which passed the House of Representatives on January 16, 2008, Congress explicitly called for MSHA to adopt smoke density and toxicity regulations. Specifically, the legislation stated, ““Not later than 90 days after the date of enactment of the S-MINER Act, the Secretary shall publish interim final rules to revise the requirements for flame resistant conveyor belts to ensure that they meet the most recent recommendations from the National Institute for Occupational Safety and Health, **and** to ensure such belts are designed to limit smoke and toxic emissions.” [Emphasis added.]

The Report language accompanying the legislation made clear that the purposed of the legislative language was to provide both smoke density and toxic gas limitations, in addition to the NIOSH-recommended BELT, in order to protect lives by reducing risks associated with the elements of fire safety; flame-resistance, smoke density, and smoke toxicity.

Specifically, the Report stated,

“The mandate and recommendations of the Technical Review Panel were confined to flame resistance. Since it began work, however, both the Panel and the Committee has been advised that belt fabric is currently available which meets not only the NIOSH flame resistance standard but which also can reduce the smoke and toxic emissions that actually lead to death in the closed environment of underground mines. Accordingly, the reported bill requires the use of belt material which can simultaneously reduce all three risks. In this sense, the reported bill is consistent with the recommendations of the Technical Review Panel but expands upon them to provide additional protections.”¹⁸

VIII. Smoke Density and Combustion Toxicity Test Results

Veyance has conducted extensive research on the smoke density and smoke toxicity of current conveyor belt samples as well as conveyor belt that is BELT-compliant. As the data below demonstrates, using off-the-shelf flame retardants, Veyance is able to meet the proposed BELT test while substantially reducing smoke density and smoke toxicity below current levels. Veyance’s research has also shown, however, that unless specifically controlled, both smoke density and smoke toxicity of BELT-compliant belting can sharply increase over current levels presenting new hazards to miners.

Veyance below is presenting: 1) smoke density data using ASTM E662; and 2) smoke toxicity data, measured in parts-per-million using Boeing Specification Support Standard BSS 7239.

¹⁸ House of Representatives, 110th Congress, 1st Session, Report 110-457, Supplemental Mine Improvement and New Emergency Response Act of 2007, p. 58.

The data is presented for three types of conveyor belts, 1) current 2G belting; 2) BELT-compliant belts using conventional halogenated flame retardants; and 3) smoke-controlled, BELT-compliant belts. Comparative tables are presented in Section D.

A. Current “2g” Conveyor Belts

1. Smoke Density (measured per ASTM E662)

Smoldering (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Current 2G compliant	2	73

Flaming (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Current 2G compliant	65	195

Ds is the calculated specific optical density as measured by ASTM E662, the test standard is attached.

2. Smoke Toxicity (measured per Boeing Specification Support Standard BSS 7239)

a. HCl

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Current 2G compliant	500	500

b. CO

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Current 2G compliant	50	500

c. HCN

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Current 2G compliant	<2	<2

d. NO_x

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Current 2G compliant	<2	5

B. Conventional Halogenated BELT-Compliant Conveyor Belts

1. Smoke Density (measured per ASTM E662)

Smoldering (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Halogenated BELT-Compliant	6	125

Flaming (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Halogenated BELT-Compliant	144	389

Ds is the calculated specific optical density as measured by ASTM E662, the test standard is attached.

2. Smoke Toxicity (measured per Boeing Specification Support Standard BSS 7239)

a. HCl

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Halogenated BELT-Compliant	1,000	1,500

b. CO

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Halogenated BELT-Compliant	50	500

c. HCN

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Halogenated BELT-Compliant	<2	2

d. NO_x

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Halogenated BELT-Compliant	<2	<2

C. Smoke-Controlled BELT-Compliant Conveyor Belts

1. Smoke Density (measured per ASTM E662)

Smoldering (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Smoke-Controlled BELT-Compliant	1	15

Flaming (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Smoke-Controlled BELT-Compliant	4	28

Ds is the calculated specific optical density as measured by ASTM E662, the test standard is attached.

2. Smoke Toxicity (measured per Boeing Specification Support Standard BSS 7239)

a. HCl

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Smoke-Controlled BELT-Compliant	6	25

b. CO

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Smoke-Controlled BELT-Compliant	10	200

c. HCN

	<u>ppm - Smoldering</u>	<u>ppm - Flaming</u>
Smoke-Controlled BELT-Compliant	<2	2

d. NO_x

	ppm - Smoldering	ppm - Flaming
Smoke-Controlled BELT-Compliant	<2	10

D. **Summary Comparison of Current, Halogenated and Smoke-Controlled Belts**

1. **Smoke Density (measured per ASTM E662)**

Smoldering (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Current 2G compliant	2	73
Halogenated BELT-Compliant	6	125
Smoke-Controlled BELT-Compliant	1	15

Flaming (avg. of 3 tests)

	<u>Ds @ 90 sec.</u>	<u>Ds @ 4 min.</u>
Current 2G compliant	65	195
Halogenated BELT-Compliant	144	389
Smoke-Controlled BELT-Compliant	4	28

Ds is the calculated specific optical density as measured by ASTM E662, the test standard is attached.

2. **Smoke Toxicity (measured per Boeing Specification Support Standard BSS 7239)**

Smoldering

	<u>HCL</u>	<u>CO</u>	<u>HCN</u>	<u>NO_x</u>
Current 2G compliant	500	50	<2	<2
Halogenated BELT-Compliant	500	10	<2	<2
Smoke-Controlled BELT-Compliant	6	10	<2	<2

Flaming

	<u>HCL</u>	<u>CO</u>	<u>HCN</u>	<u>NO_x</u>
Current 2G compliant	500	500	<2	5
Halogenated BELT-Compliant	1,500	500	2	<2
Smoke-Controlled BELT-Compliant	25	200	2	10

E. Test Conclusions

- ◆ Increasing conveyor belt flame-retardant quantities to meet the proposed BELT test has the potential to substantially increase the density and toxicity of smoke given off in both smoldering and burning (passing the BELT does **not** mean that the belting is fire proof) conditions.
- ◆ When controlling smoke through widely available, cost-competitive flame retardants, smoke can be reduced well below current levels while still meeting the proposed BELT flame resistance standard.
- ◆ To ensure that underground miners are afforded improved safety, MSHA needs to specifically mandate limits on: 1) flame-resistance; and 2) smoke density.

IX. Test Methodologies Used by Veyance and Federal Agencies

All of the tests discussed above, were conducted using laboratory-scale consensus standard methodologies that are also used by federal agencies.

1. **ASTM E662**

ASTM E662 is a very widely used standard test to measure the optical density of smoke. A copy of the ASTM E662 standard is attached as Appendix A of these comments.

Fire safety regulations using ASTM E662 have already been established by the Department of Transportation's Federal Railroad Administration.¹⁹ The Federal Aviation Administration also uses a similar ASTM smoke density testing standard (with a slight variation on the sample holder) for cabin materials in commercial aircraft.

It should be noted that ASTM E662 is very similar to the National Fire Protection Association's standard NFPA 258. NFPA has explained that they recommended that NFPA 258 be withdrawn because: 1) of the widespread regulatory use of ASTM E662; and 2) unlike the ASTM standard, the NFPA standard lacked enforceable language.

As NFPA explained, "In its current form NFPA 258 cannot be used as a mandatory reference. ASTM E662 is similar to NFPA 258 and is referenced in numerous regulator documents. NFPA 258 includes the caveat that it is for research purposes only and it is written as a Recommended Practice without enforceable language. In light of current harmonization efforts regarding fire test standards with ASTM and UL, the committee finds no compelling reason to revise NFPA 258 into a standard particularly when a similar test method maintained by ASTM currently exists."²⁰

In discussing the use of E662 and other standard fire safety tests by the Navy, the National Academy of Sciences (NAS) made a crucial point that corroborates Veyance's fundamental approach to underground fire safety – no single test is adequate for evaluating the fire hazards associated with any material. As the NAS explained, "No single metric, and hence no one test method, is adequate to completely evaluate the fire hazard of a particular material system. For example, the testing procedure for evaluating composite material systems for naval submarine interiors (DOD, 1991) includes oxygen-temperature index, flame spread (ASTM E-162), ignitability (ASTM E-1354), heat release (ASTM E-1354), smoke obscuration (ASTM E-662), combustion gas generation (ASTM E-1354), and toxicity (N-gas method)."²¹

Veyance strongly recommends that MSHA accept the long-standing recognition by the Department of Transportation, Department of Defense, and the National Academy of Sciences—no single test can adequately measure for the fire protection

¹⁹ 67 Fed Reg 42911, June 25, 2002.

²⁰ NFPA, Report on Proposals A2006, found at <http://www.nfpa.org/assets/files/PDF/ROP/258-A2006-ROP.pdf>. [Emphasis added.]

²¹ National Materials Advisory Board, the National Academies, "Fire- and Smoke-Resistant Interior Materials for Commercial Transport Aircraft," 1995, p. 27.

needed to protect human lives, multiple tests are needed to measure the different aspects of a material's fire safety characteristics including flame-resistance and smoke toxicity. It is only by adopting smoke density regulations, based on existing Department of Transportation standards, along with flame-resistance standards, that MSHA will be able to provide appropriate protection to underground miners.

2. **BSS 7239**

Boeing Specification Support Standard BSS 7239 is standard methodology for measuring the toxic compounds in smoke. A copy of BSS 7239 is attached to these comments as Appendix B.

The Federal Aviation Administration references BSS 7239 in their Aircraft Materials Fire Test Handbook.²²

3. **ASTM E1354**

ASTM 1354 is a standard testing methodology for measuring smoke and heat release from materials using a frequently-used laboratory testing device called a "cone calorimeter." A copy of ASTM E1354 is attached to these comments as Appendix C.

NASA makes use of the ASTM E1354 standard in their procurement requirements.²³ The Nuclear Regulatory Commission described the standard as the "most common method to measure HRR [Heat Release Rate]."²⁴

X. Other Uses of Smoke Toxicity and Density Safety Regulations: Airbus

Twenty-five years ago, the European aircraft manufacturer Airbus established, based on US Federal Aviation Administration requirements, requirements for both smoke density and smoke toxicity. Since then, Airbus has strengthened their requirements to protect passengers from smoke and fumes, as well as flames, in event of an accident.

As Airbus explains, "In 1979 Airbus established the ATS 1000.001 (Airbus Test Specification) representing an extended in-house version of the FAA regulations with regard to smoke and toxicity requirements. ... In 1994 the ATS 1000.001 was superseded by the ABD 0031. The

²² http://www.fire.tc.faa.gov/pdf/handbook/00-12_apE.pdf.

²³

http://standards.gov/sibr/query/index.cfm?fuseaction=Home.procurement_sibr_by_keyword&Keyword_Input=e1354&CFID=16403332&CFTOKEN=52cd976356d1b8fe-A4336247-F2AD-EE93-E413BA0BFE97124A&jsessionid=b4303544fb29b3a211f1

²⁴ Fire Dynamics Tools (FDT[®]) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program (NUREG-1805, Final Report), p. 3-3.

ABD 0031 represents an increased FST standard such as more severe smoke emission limits for all non-metallic interior components.”²⁵

XI. The Phase-Out of Halogenated Materials

Companies in Europe and the US are phasing-out or have already eliminated the use halogenated materials for flame retardant purposes because modern alternatives result in less hazardous smoke (density and toxicity) and halogen-free fire retardants are more environmentally friendly.

The European Union, in a 2000 decision regarding the proposed merger of two companies producing materials used in flame retardants, summarized the smoke density, smoke toxicity and environmental concerns regarding halogenated flame retardants, “There is another category of alternative flame-retardant substances for the above applications, namely, halogenated flame retardants. Halogenated substances may be efficient flame retardants; however, they are toxic and generate more smoke than inorganic flame retardants. Because of growing environmental concerns — which are expected to lead to the phasing-out of those substances — halogenated phosphorous substances are being replaced by inorganic flame retardants...”²⁶

A European Union official in 2006 discussing a “*Draft Commission Decision regarding the Classification of the Reaction to Fire Performance of Construction Products*,” before a World Trade Organization Committee, explained that “member States would be allowed to require for certain works the use of electric cables belonging to a so called “low smoke/low/zero halogen” family which would prevent incapacitating effects to occupants allowing them therefore enough time to escape in case of fire and the spread of toxic gases.”²⁷

A recent trade magazine article discussing the global shift to halogen-free flame retardants noted that “Two key compliance areas for additives have been... and growth of halogen-free flame retardant (HFFR) systems. Revisions made in 2006 to the EU’s Construction Products Directive (CPD) raise EU fire safety standards and change the regulatory focus to a product performance target. The CPD revisions are expected to drive use of HFFR with better flame retardant performance...” The article also explains that “Regulatory concerns and pressure from non-governmental organizations (NGOs) are driving a move to halogen-free flame retardants (HFFR), say suppliers. In building and construction, Europe has already switched mainly to HFFR constructions... China and India are also

²⁵ Theo Klems, Airbus S.A.S., UP-DATE ON AIRBUS FIRE SAFETY RESEARCH AND DEVELOPMENT, found at http://www.fire.tc.faa.gov/2004Conference/files/fire/T.Klems_Airbus_Fire_Safety_R&D.pdf.

²⁶ Official Journal of the European Communities, Commission Decision of 14 March 2000, found at <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:090:0001:0022:EN:PDF>, para. 19. {Emphasis added.}

²⁷ World Trade Organization, Committee on Technical Barriers to Trade, Minutes of Meeting of 15 and 17 March 2006, para 21, found at http://trade.ec.europa.eu/doclib/docs/2008/january/tradoc_137570.pdf

converting to low-smoke, zero halogen (LS0H) formulations, say experts. ... Low smoke generation is a global concern, particularly in building and construction applications.”²⁸

Specific standardized test methods used in Europe with respect to wire and cable include prEN 50399-2-1 and prEN 50399-2-2 “Common test methods for cables under fire conditions – Heat release and smoke production measurement on cables during flame spread test” Other test standards include “EN 61034-2 Measurement of smoke density of cables burning under defined conditions” and “ISO 5660 Reaction-to-fire tests – Heat release, smoke production and mass loss rate.”

Among American companies, Intel has announced that the company “is introducing halogen-free packaging technology for its processor and chipset products starting in 2008, and will convert most of its 45nm processor and 65nm chipset products to halogen-free packaging technology by the end of 2008.”²⁹ Intel also announced a symposium earlier this year in partnership with IPC/Association Connecting Electronics Industries, as part of “Intel’s effort to eliminate halogenated fire retardants from our product packaging as part of a broader strategy to support an environmentally sustainable future....”³⁰ The significance of the computer industries announcement is to underscore that halogenated flame retardants are being replaced in diverse industries.

Veyance Conclusions

1. No single test methodology is adequate for measuring all three critical elements of fire safety needed to protect the safety of underground miners. Instead separate standards are needed for:
 - A. Flame-resistance; and
 - B. Smoke density.
2. Non-proprietary materials are currently available which allow conveyor belts to meet the NIOSH-recommended BELT flame-resistance standard while simultaneously reducing smoke toxicity and smoke density below current levels.
 - Belts made with non-halogenated low-smoke flame retardants have similar durability and other performance criteria to belts made with high-smoke halogenated materials.
 - Belts made with non-halogenated low-smoke flame retardants are able to pass drum friction tests.

²⁸ Plastics Additives & Compounding, “Regulatory issues drive developments in wire and cable,” *July/August 2007*, pp. 32-33.

²⁹ <http://www.intel.com/technology/silicon/leadfreetech/overview.htm>.

³⁰ <http://www.pcb007.com/anm/templates/article.aspx?articleid=17309&zoneid=77&v=>.



3. Low-smoke BELT-compliant conveyor belts cost no more than high-smoke BELT-compliant conveyor belts.

Veyance Recommendation

MSHA should quickly and simultaneously adopt regulations controlling conveyor flame-resistance and smoke density. MSHA should also adopt a drum friction test on a speedy basis.

Sincerely,

Terry Graber
Global Technical Manager, HW Conveyor Belt
Veyance Technologies, Inc.

08-15-08

Dave Maguire
Vice President, Global Technology
Veyance Technologies, Inc.

08-15-08

**APPENDIX A:
ASTM E662**



Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials¹

This standard is issued under the fixed designation E 662; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This fire-test-response standard covers determination of the specific optical density of smoke generated by solid materials and assemblies mounted in the vertical position in thicknesses up to and including 1 in. (25.4 mm).

1.2 Measurement is made of the attenuation of a light beam by smoke (suspended solid or liquid particles) accumulating within a closed chamber due to nonflaming pyrolytic decomposition and flaming combustion.

1.3 Results are expressed in terms of specific optical density which is derived from a geometrical factor and the measured optical density, a measurement characteristic of the concentration of smoke.

1.4 This test method is intended for use in research and development and not as a basis for ratings for regulatory purposes.

1.5 *This standard measures and describes the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products or assemblies under actual fire conditions.*

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.7 The values stated in inch-pound units are to be regarded as standard. Values stated in parentheses are for information only.

2. Referenced Documents

2.1 ASTM Standards:²

D 2843 Test Method for Density of Smoke from the Burn-

ing or Decomposition of Plastics
E 176 Terminology of Fire Standards

3. Terminology

3.1 *Definitions*—For definitions of terms found in this test method refer to Terminology E 176.

4. Summary of Test Method

4.1 This test method employs an electrically heated radiant-energy source mounted within an insulated ceramic tube and positioned so as to produce an irradiance level of 2.2 Btu/s-ft² (2.5 W/cm²) averaged over the central 1.5-in. (38.1-mm) diameter area of a vertically mounted specimen facing the radiant heater. The nominal 3 by 3-in. (76.2 by 76.2-mm) specimen is mounted within a holder which exposes an area measuring 2 $\frac{1}{16}$ by 2 $\frac{1}{16}$ in. (65.1 by 65.1 mm). The holder is able to accommodate specimens up to 1 in. (25.4 mm) thick. This exposure provides the nonflaming condition of the test.

4.2 For the flaming condition, a six-tube burner is used to apply a row of equidistant flamelets across the lower edge of the exposed specimen area and into the specimen holder trough. This application of flame in addition to the specified irradiance level from the heating element constitutes the flaming combustion exposure.

4.3 The test specimens are exposed to the flaming and nonflaming conditions within a closed chamber. A photometric system with a vertical light path is used to measure the varying light transmission as smoke accumulates. The light transmittance measurements are used to calculate specific optical density of the smoke generated during the time period to reach the maximum value.³

5. Significance and Use

5.1 This test method provides a means for determining the specific optical density of the smoke generated by specimens of materials and assemblies under the specified exposure conditions. Values determined by this test are specific to the specimen or assembly in the form and thickness tested and are

¹ This test method is under the jurisdiction of ASTM Committee E05 on Fire Standards and is the direct responsibility of Subcommittee E05.21 on Smoke and Combustion Products.

Current edition approved July 15, 2006. Published August 2006. Originally approved in 1979. Last previous edition approved in 2005 as E 662 – 05.

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ Additional parameters, such as the maximum rate of smoke accumulation, time to a fixed optical density level, or a smoke obscuration index provide potentially useful information. See Appendix X1.

not to be considered inherent fundamental properties of the material tested. Thus, it is likely that closely repeatable or reproducible experimental results are not to be expected from tests of a given material when specimen thickness, density, or other variables are involved.

5.2 The photometric scale used to measure smoke by this test method is similar to the optical density scale for human vision. However, physiological aspects associated with vision are not measured by this test method. Correlation with measurements by other test methods has not been established.⁴

5.3 At the present time no basis is provided for predicting the density of smoke generated by the materials upon exposure to heat and flame under other fire conditions.

5.4 The test method is of a complex nature and the data obtained are sensitive to variations which in other test methods might be considered to be insignificant (see Section 6). A precision statement based on the results of a roundrobin test by a prior draft version of this test method is given in 1.4.1

5.5 In this procedure, the specimens are subjected to one or more specific sets of laboratory test conditions. If different test conditions are substituted or the end-use conditions are changed, it is not always possible by or from this test method to predict changes in the fire-test-response characteristics measured. Therefore, the results are valid only for the fire test exposure conditions described in this procedure.

6. Limitations

6.1 If during the test of one or more of the three replicate samples there occurs such unusual behavior as (1) the specimen falling out of the holder, (2) melted material overflowing the sample holder trough, (3) self-ignition in the pyrolysis mode, (4) extinguishment of the flame triplets (even for a short period of time), or (5) a specimen being displaced from the zone of controlled irradiance, then an additional three samples of the identical preconditioned materials shall be tested in the test mode in which the unusual behavior occurred. Data obtained from the improper tests noted above shall not be incorporated in the averaged data but the occurrence shall be reported. The test method is not suitable if more than three of the six replicates tested show these characteristics.

6.2 The test method has proven sensitive to small variations in sample geometry, surface orientation, thickness (either overall or individual layer), weight, and composition. It is, therefore, critical that the replicate samples be cut, sawed, or blanked to identical sample areas, 3 by 3, +0, -0.03 in. (76.2 by 76.2, +0, -0.8 mm), and that records be kept of the respective weights with the individual test data. It is feasible that evaluation of the obtained data together with the individual weights will assist in assessing the reasons for any observed variability in measurements. Preselection of samples with identical thickness or weight, or both, are potential methods to

reduce the variability but are likely to not be truly indicative of the actual variability to be expected from the material as normally supplied.

6.3 The results of the test apply only to the thickness of the specimen as tested. There is no common mathematical formula to calculate the specific optical density of one thickness of a material when the specific optical density of another thickness of the same material is known.

6.4 The test method is sensitive to small variations of the position of the specimen and radiometer relative to the radiant heat source.

6.5 It is critical to clean the test chamber, and to remove accumulated residues from the walls when changing from one test material to another, to ensure that chemical or physical recombination with the effluents or residues produced does not affect the data obtained. Even when testing the same material, excessive accumulations of residue shall not be permitted to build up since ruggedness tests have indicated that such accumulations serve as additional insulators tending to reduce normally expected condensation of the aerosol, thereby raising the measured specific optical density.

6.6 With resilient samples, take extreme care to ensure that each replicate sample in its aluminum foil wrapper is installed so that each protrudes identically through the front sample holder opening. Unequal protrusion will subject the samples to different effective irradiances and to slightly different ignition exposures. Excessive protrusion of specimens has the potential to cause drips or for the specimen to sag onto the burner, clogging the flame jets and thereby invalidating the test.

6.7 The measurements obtained have also proven sensitive to small differences in conditioning (see Section 9). Many materials such as carpeting and thick sections of wood, plastics, or plywood require long periods to attain equilibrium (constant weight) even in a forced-draft humidification chamber.

7. Apparatus

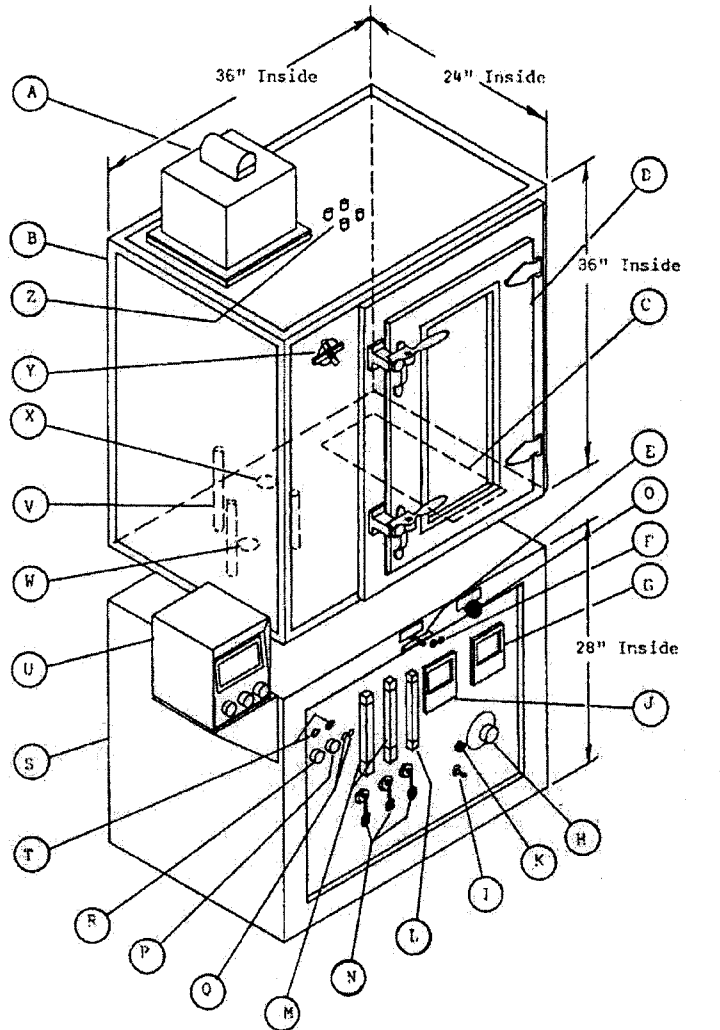
7.1 Fig. 1 shows examples of the test apparatus, with a detailed description contained in the remainder of Section 7 and in Annex A2. The apparatus shall include the following:

7.1.1 *Test Chamber*—As shown in Fig. 1, the test chamber shall be fabricated from laminated panels⁵ to provide inside dimensions of 36 by 24 by 36 ± 1/8 in. (914 by 610 by 914 ± 3 mm) for width, depth, and height, respectively. The interior surfaces shall consist of porcelain enameled metal, or equivalent coated metal resistant to chemical attack and corrosion, and suitable for periodic cleaning. Sealed windows shall be provided to accommodate a vertical photometric system. All other chamber penetrations shall be sealed. When all openings are closed, the chamber shall be capable of developing and maintaining positive pressure during test periods, in accordance with 11.11.

7.1.2 *Radiant Heat Furnace*—As shown in Fig. 2, an electric furnace with a 3-in. (76.2-mm) diameter opening shall

⁴ Other test methods for measuring smoke available at the time of the publications referenced have been reviewed and summarized in "The Control of Smoke in Building Fires—A State of the Art Review," *Materials Research and Standards*, Vol 42, April 1971, pp. 16-23 and "A Report on Smoke Test Methods," *ASTM Standardization News*, August 1976, pp. 18-26.

⁵ Commercially available panels of porcelain-enameled steel (interior surface) permanently laminated to an asbestos-magnesia core and backed with galvanized steel (exterior surface), total thickness 3/8 in. (9.6 mm), have been found suitable.

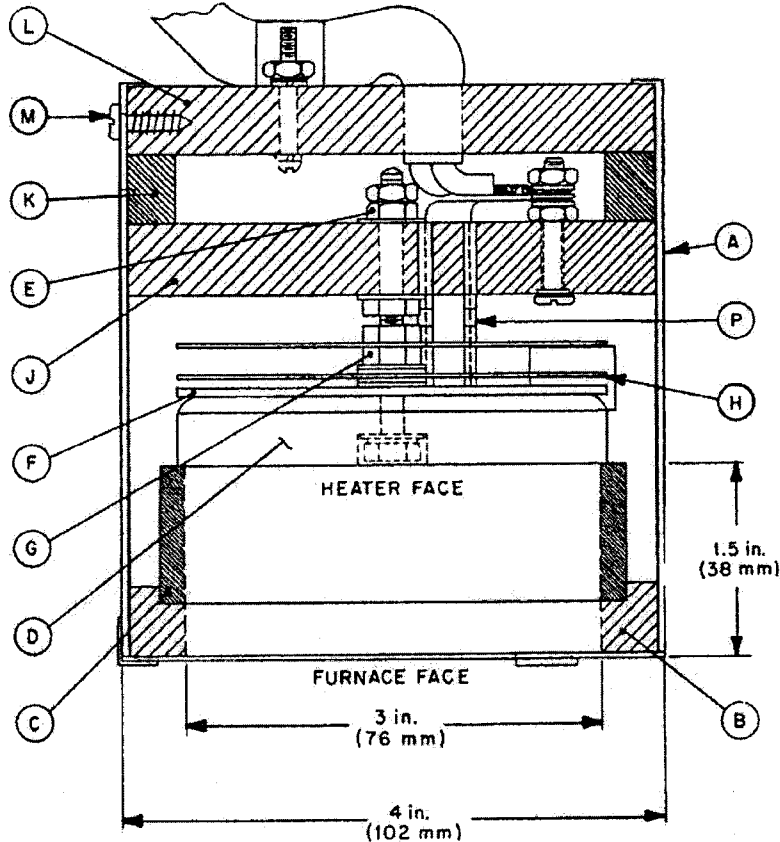


- | | |
|--|-------------------------------------|
| A—Photomultiplier tube housing | N—Flowmeter shutoff valves |
| B—Chamber | O—Sample mover knob |
| C—Blow-out panel (in floor of chamber) | P—Light source switch |
| D—Hinged door with window | Q—Light source voltage jacks |
| E—Exhaust vent control | R—Line switch |
| F—Radiometer output jacks | S—Base cabinet |
| G—Temperature (wall) indicator | T—Indicating lamps |
| H—Autotransformer | U—Microphotometer (photomultiplier) |
| I—Furnace switch | V—Optical system rods |
| J—Voltmeter (furnace) | W—Optical system floor window |
| K—Fuse holder (furnace) | X—Exhaust vent damper |
| L—Radiometer air flowmeter | Y—Inlet vent damper |
| M—Gas and air (burner) flowmeter | Z—Access ports |

FIG. 1 Smoke Density Chamber Assembly

be used to provide a constant irradiance on the specimen surface. The furnace shall be located along the centerline equidistant between the front and back of the chamber, with the opening facing toward and about 12 in. (305 mm) from the right wall. The centerline of the furnace shall be about 7¼ in. (195 mm) above the chamber floor. The furnace control system shall maintain the required irradiance level, under steady-state

conditions with the chamber door closed, of 2.20 ± 0.04 Btu/ft²·s (2.50 ± 0.05 W/cm²) for 20 min. The control system shall consist of an autotransformer or alternative control device, and a voltmeter or other means for monitoring the electrical input. Where line voltage fluctuations exceed ± 2.5 , a constant voltage transformer is required to maintain the prescribed irradiance level.



- | | |
|----------------------------------|----------------------------------|
| A—Stainless steel tube | G—Stainless steel spacers |
| B—Front insulating ring | H—Stainless steel reflectors (3) |
| C—Ceramic tube | J—Center insulating disk |
| D—Heater/plate 525 W | K—Insulating spacer ring |
| E—Stainless steel mounting screw | L—Rear insulating disk |
| F—Insulating gasket | M—Sheet metal screw (2) |
| | P—Heater leads/porcelain beads |

FIG. 2 Furnace Section

7.1.3 *Specimen Holder*—Specimen holders shall conform in shape and dimension to that shown in Fig. 3 and be fabricated to expose a $2\frac{1}{16}$ by $2\frac{1}{16}$ -in. (65.1 by 65.1-mm) specimen area. Also shown in Fig. 3 are the spring and rods for retaining the specimen within the holders.

7.1.4 *Framework for Support of Furnace and Specimen Holder*—The furnace and specimen supporting framework shall be constructed essentially in accordance with Fig. 4.

7.1.5 *Photometric System*—The photometric system shall consist of a light source and photodetector, oriented vertically to reduce measurement variations resulting from stratification

of the smoke generated by materials under test. The system shall be as shown in Figs. 5 and 6 and include the following:

7.1.5.1 The light source shall be an incandescent lamp operated at a fixed voltage in a circuit powered by a constant-voltage transformer. The light source shall be mounted in a sealed and light-tight box. This box shall contain the necessary optics to provide a collimated light beam passing vertically through the chamber. The light source shall be maintained at an operating voltage required to provide a brightness temperature of $2200 \pm 100^\circ\text{K}$.

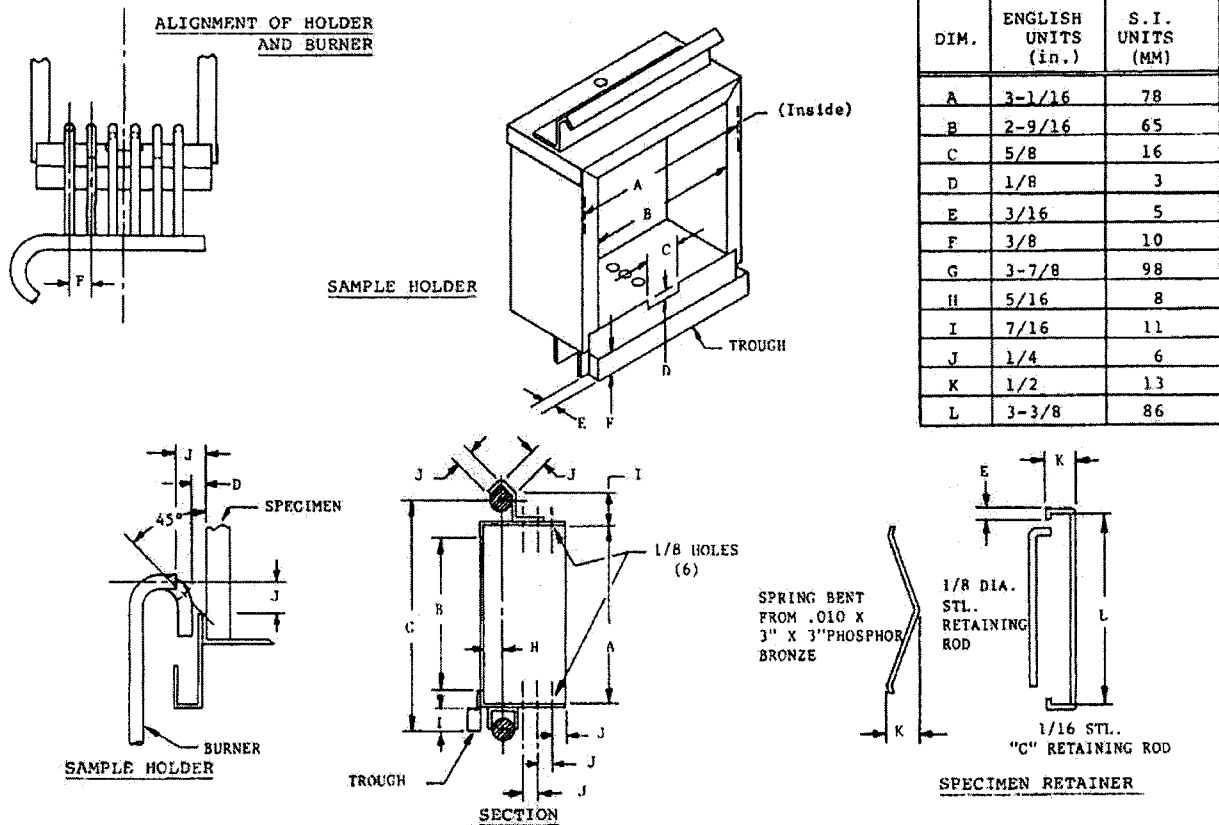


FIG. 3 Details of Specimen Holder and Pilot Burner

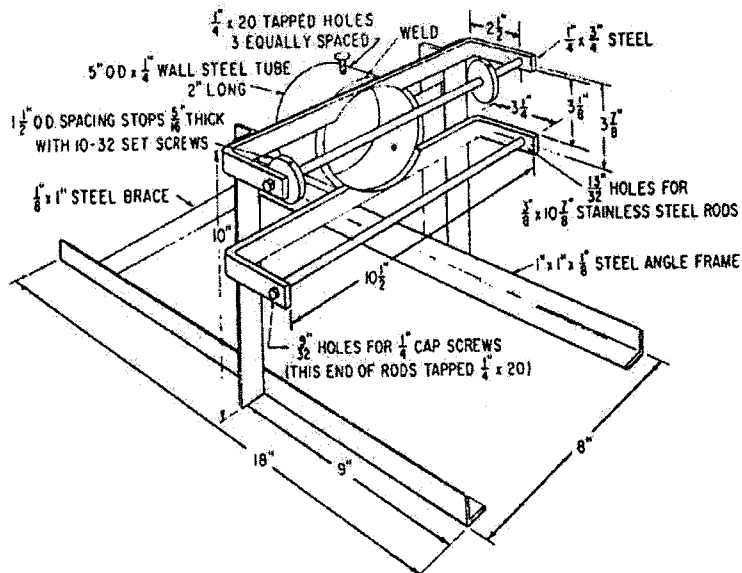
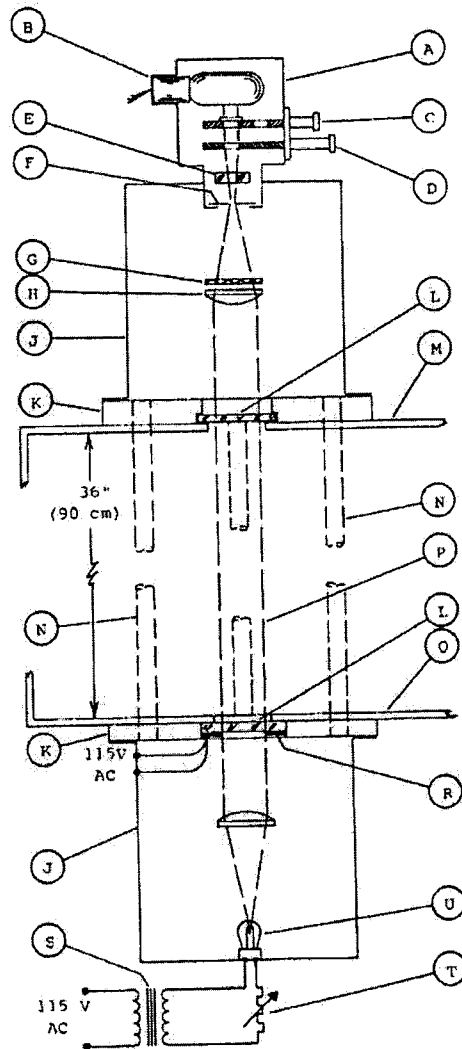


FIG. 4 Furnace Support

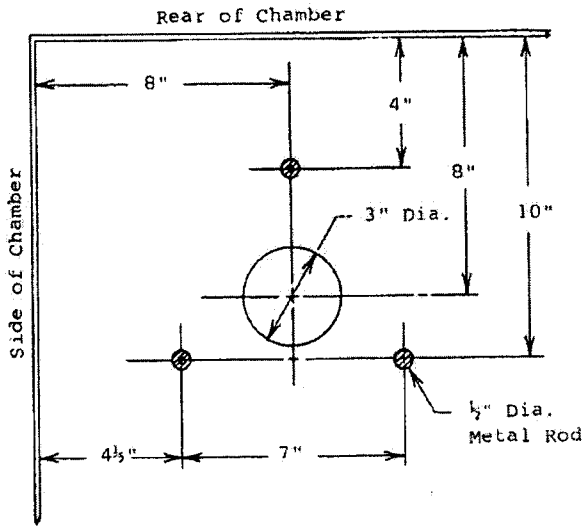


- | | |
|---|---|
| <p>A—Photomultiplier housing
 B—Photomultiplier tube and socket
 C—Upper shutter blade, with ND2 filter over one aperture
 D—Lower shutter blade, with single aperture
 E—Opal diffuser filter
 F—Aperture disk
 G—Neutral density compensating filter (from set of 9)
 H—Lens, 7 diopter (2)
 J—Optical system housing (2)</p> | <p>K—Optical system platforms (2)
 L—Optical windows (2)
 M—Chamber roof
 N—Alignment rods (3)
 P—Parallel light beam, 1.5-in. (37.5-mm) diameter
 O—Chamber floor
 R—Optical window heater, silicone-fiberglass 50 W/115 V
 S—Regulated light source transformer, 115/125 V-6 V
 T—Adjustable resistor, light source, adjusted for 4 V
 U—Light source</p> |
|---|---|

FIG. 5 Photometer Details

7.1.5.2 The photodetector shall be a photomultiplier tube, with an S-4 spectral sensitivity response and a dark current less than 10^{-9} A. A set of nine gelatin compensating filters varying from 0.1 to 0.9 neutral density are mounted one or more as required in the optical measuring system to correct for differences in the luminous sensitivity of the photomultiplier tube. These filters also provide correction for light source or photomultiplier aging and reduction in light transmission, through

discolored or abraded optical windows. An additional criterion for selection of photomultiplier tubes requires a minimum sensitivity equivalent to that required to give a full scale reading with only the No. 5 compensating filter in the light path. A light-tight box located directly opposite the light source shall be provided to mount the photodetector housing and the associated optics. A glass window shall be used to isolate the photodetector and its optics from the chamber atmosphere.



OPTICAL SYSTEM LOCATION
plan view
FIG. 6 Photometer Location

7.1.5.3 In addition to the above compensating filter, a neutral density range extender filter permitting the system to measure to Optical Density 6 is incorporated in the commercial version of the smoke density chamber. The accuracy of read-outs in the range above D_v 528 is affected by the excessive light scattering present in such heavy smoke concentration.

Where D_v values over 500 are measured, it is necessary to provide a chamber window cover to prevent room light from being scattered into the photomultiplier, thereby providing an incorrect higher transmission value.

7.1.6 Radiometer—The radiometer for standardizing the output of the radiant heat furnace shall be of the circular foil type, the operation of which was described by Gardon.⁶ The construction of the radiometer shall be as shown in Fig. 7. It shall have a stainless steel reflective heat shield with a 1½-in. (38.1-mm) aperture on the front and a finned cooler supplied with compressed air mounted on the rear to maintain a constant body temperature of $200 \pm 5^\circ\text{F}$ ($93 \pm 3^\circ\text{C}$).

7.1.7 Thermocouple—A thermocouple shall be fixed to the center of the inner surface of the wall opposite the door.

7.1.8 Output Instrumentation—The outputs of the radiometer shall be measured using a potentiometer and the results recorded. The photodetector output shall be measured with a potentiometer or other suitable instrument capable of measurement over the range of the apparatus. See Annex A1.

7.1.9 Manometer for Chamber Pressure Measurements —A simple water manometer with a range up to 6 in. (152 mm) of water shall be provided to monitor chamber pressure and leakage. The pressure measurement point shall be through a gas-sampling port in the chamber. A simple water column or relief valve shall be provided to permit control of chamber pressure (see A2.8).

⁶Gardon R., "An Instrument for the Direct Measurement of Intense Thermal Radiation." *Review of Scientific Instruments*, Vol 24, 1953, pp. 366-370.

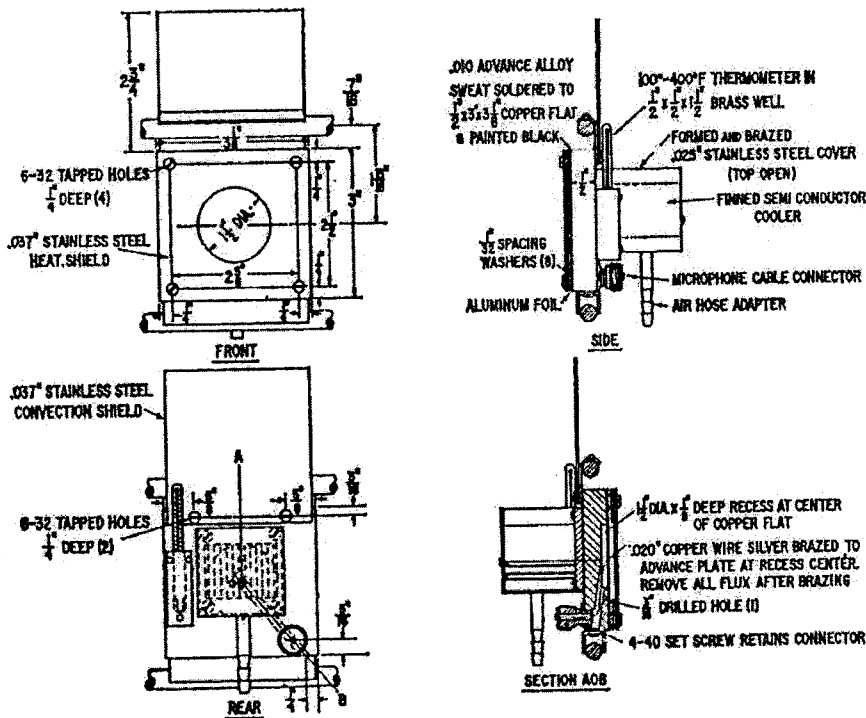


FIG. 7 Radiometer Details

7.1.10 *Multiple Flamelet Burner*—For a flaming exposure test, a six-tube burner, with construction details as shown in Fig. 3, shall be used. The burner shall be centered in front of and parallel to the specimen holder. The tips of the two horizontal tubes shall be centered $\frac{1}{4} \pm \frac{1}{16}$ in. (6.4 ± 1.5 mm) above the lower opening of the specimen holder and $\frac{1}{4} \pm \frac{1}{32}$ in. (6.4 ± 0.8 mm) away from the face of the specimen surface. Provision shall be made to rotate or move the burner out of position during nonflaming exposures. The fuel shall be propane having a 95 % purity or better. Filtered oil-free air and propane shall be fed through calibrated flowmeters and needle valves at 500 cm³/min for air and 50 cm³/min for the propane and premixed prior to entry into burner.

7.1.10.1 It is possible that sample drippings or residue will cause constrictions (or even completely seal) the small openings in the individual burner tiplets unless the test residues are immediately removed while still warm and viscous. One way to correct or prevent this situation, is for the user to prepare a set of six tempered spring steel wires each approximately $3\frac{1}{2}$ in. (89 mm) long fabricated from 30-gage (0.014 in.) wire, with one end crimped or brazed to a knob to facilitate handling and to prevent possible loss of the wire by complete insertion. When a burner tiplet becomes clogged as indicated by flame extinguishment and inability to relight or by a distorted flame shape, thus invalidating the test, insert one of the wires and work it through several times to clear the obstruction. Immediately upon removal of the burner from the chamber while still warm, insert all six wires in a like manner but leave them in place until the next time the burner is used. Where residues and clogging persist, prepare a suitable solvent bath so as to immerse the complete burner and use the wires to loosen any hardened residue. Because of the construction, it is impossible to service the individual burner tiplets from the opposite direction, but because of ratio of diameters any obstruction pushed through the small diameter tiplets is likely to readily drop through the large diameter body tubing. Since most of these solvents are hazardous, take proper precautions for handling and protection of personnel. If flammable solvents are used, take care to ensure that "hot" burners are not immersed until cooled to room temperature.

8. Test Specimens

8.1 *Size*—The test specimens shall be 3 by 3, +0, -0.03 in. (76.2 by 76.2, +0, -0.8 mm) by the intended installation thickness up to and including 1 in. (25.4 mm). Materials greater than 1 in. (25.4 mm) thick shall be sliced to 1-in. (25.4-mm) thickness, and each original (uncut) surface tested separately if required under 8.3.1. The results are valid only for the thickness and form in which it is tested.

8.2 *Specimen Orientation*—If visual inspection of a material indicates a pronounced grain pattern, process-induced orientation or other nonisotropic property, a minimum of three specimens shall be tested for each orientation in each test mode. Exception: Where data are available and to show that orientation of a specimen has no significant effect on test results, the specimen is only required to be tested in one orientation with each test mode (Note 1). When specimens require testing in different orientations, results of tests for each orientation shall be reported separately. Test results from

specimens tested under different orientations shall not be used to obtain average values.

NOTE 1—It has been shown the orientation of carpet test specimens in terms of length and width (parallel and perpendicular to manufactured direction) has no statistically significant effect on the specific optical density obtained using this test method (1).⁷

8.3 Specimen Assembly:

8.3.1 The specimen shall be representative of the materials or composite and shall be prepared in accordance with recommended application procedures. Flat sections of the same thickness and composition are to be tested rather than curved, molded, or specialty parts. Substrate or core materials for the test specimens shall be the same as those for the intended application. If a material or assembly has the potential to be exposed to a fire on either side, both sides shall be tested. If an adhesive is intended for field application of a finish material or substrate, the prescribed type of adhesive and the spreading rate recommended for the assembly of test specimen shall be used and reported.

8.3.1.1 Finish materials, including sheet laminates, tiles, fabrics, and others secured to a substrate material with adhesive, and composite materials not attached to a substrate, have the potential to be subject to delamination, cracking, peeling, or other separations affecting their smoke generation. To evaluate these effects, it is often necessary to perform supplementary tests on a scored (split) exposed surface, or on interior layers or surfaces. When supplementary tests are conducted for this purpose, the manner of performing such supplementary tests, and the test results, shall be included in the report with the conventional test results.

8.3.2 For comparative tests of finish materials without a normal substrate or core, and for screening purposes only, the following procedures shall be employed:

8.3.2.1 Rigid or semirigid sheet materials shall be tested by the standard procedure regardless of thickness.

8.3.2.2 In the absence of a specified assembly system, paints, adhesives, etc., intended for application to combustible base materials, shall be applied to the smooth face of $\frac{1}{4}$ -in. (6.4-mm) thick tempered hardboard, nominal density 50 to 60 lb/ft³ (800 to 960 kg/m³), using recommended (or practical) application techniques and coverage rates. Tests shall also be conducted on the hardboard alone, and these values shall be recorded as supplemental to the measured values for the composite specimen.

8.3.2.3 Paints, adhesives, etc., intended for application to noncombustible substrate materials, shall be applied to the smooth face of $\frac{1}{4}$ -in. (6.4-mm) thick inorganic reinforced cement board, nominally 110 ± 10 lb/ft³ (1762 ± 160 kg/m³) in density, using recommended (or practical) application techniques and coverage rates.

8.3.2.4 If fabrics or thin flexible films tend to shrink, to bunch, to blister, or to pull out from under the specimen holder during the test, the three test specimens shall be stapled with its aluminum foil wrapper to the inorganic insulation millboard

⁷ The boldface numbers in parentheses refer to the list of references at the end of this standard.

backing. Five wire staples,⁸ approximately ½ by ¼ by 0.02 in. (12.7 by 6.3 by 0.5 mm),⁹ shall be positioned horizontally at the center, and at the center of the four quadrants.⁸

8.3.3 Specimen Mounting:

8.3.3.1 All specimens shall be covered across the back, along the edges, and over the front surface periphery with a single sheet of aluminum foil (0.001 ± 0.0005 in. or approximately 0.04 mm) with the dull side in contact with the specimen. Care shall be taken not to puncture the foil or introduce unnecessary wrinkles during the wrapping operation. Fold in such a way so as to minimize losses of melted material at the bottom of the holder. Excess foil along the front edges shall be trimmed off after mounting. A flap of foil shall be cut and bent forward at the spout to permit flow from melting specimens.

8.3.3.2 All specimens shall be backed with a sheet of ½-in. (12.7-mm) thick inorganic insulation millboard. The specimen and its backing shall be secured with the spring and retaining rod. A modified C-shape retaining rod or similar device shall be used with specimens from ¾ to 1 in. (16 to 25 mm) thick. Do not deform compressible specimens below their normal thickness.

9. Conditioning

9.1 Predry specimens for 24 h at 140 ± 5°F (60 ± 3°C) and then condition to equilibrium (constant weight) at an ambient temperature of 73 ± 5°F (23 ± 3°C) and a relative humidity of 50 ± 5 % (see 6.7).

9.2 While in the conditioning chamber, specimens shall be supported in racks so that air has access to all surfaces. Forced-air movement in the conditioning chamber will assist in accelerating the conditioning process.

10. Number of Test Specimens

10.1 Conduct three tests under flaming exposure and three tests under nonflaming exposure on each material (total of six specimens) in accordance with the conditions described herein.

10.1.1 When any result in any set of three replicates is such that it exceeds the minimum result by 50 % for no apparent reason, test an additional set of three replicates and report the average of all six results.

10.1.2 Where one or more of the three replicate tests demonstrate an unusual behavior such as detailed in 6.1, test three additional replicates. Average only the data from the successful tests.

10.2 Prior to use in a test, record the weight of each sample. Comparison of the weights with the individual optical density results has the potential to assist in assessing the reasons for the variability in measurements.

11. Procedure

11.1 Conduct all tests in a room or enclosed space having an ambient temperature of 73 ± 5°F (23 ± 3°C) and relative humidity of approximately 50 % at the time of test. Take

precautions to provide a means for removing potentially hazardous gases from the area of operation.

11.1.1 Caution is urged during use of apparatus to prevent explosion of pyrolyzates, particularly under nonflaming conditions. Good laboratory procedure is urged also to prevent exposure of the operator to smoke, particularly during removal of the sample from the chamber or in clean-up.

11.2 Clean the chamber walls whenever periodic visual inspection indicates the need.⁹ Clean the exposed surfaces of the glass windows separating the photodetector and light source housing from the interior of the chamber, before each test (ethyl alcohol is generally effective). Charred residues on the specimen holder and horizontal rods shall be removed between tests to avoid contamination.

11.3 During the warm-up period all electric systems (furnace, light source, photometer readout, etc.) shall be on, the exhaust vent and chamber door closed, and the inlet vent open. When the temperature on the center surface of the back wall reaches a steady-state value in the range of 95 ± 4°F (35 ± 2°C) the chamber is ready for furnace calibrating or testing. To increase chamber wall surface temperature to the stated level it is permissible for an auxiliary heater to be used but it shall be removed prior to performing tests; conversely to decrease this temperature, the exhaust blower is a useful tool to introduce cooler air from the laboratory. Standardize the furnace output irradiance at periodic intervals according to test experience (normally twice per test day).

11.4 A "blank" specimen holder, with the inorganic insulation millboard backing exposed shall always be directly in front of the furnace except when displaced to the side by (1) the specimen holder during a test or (2) the radiometer during calibration. It shall be returned immediately to this position when testing or calibration is completed to prevent excessive heating of the adjacent wall surface.

11.5 During the calibration, place the radiometer on the horizontal rods of the furnace support framework and accurately position in front of the furnace opening, by sliding and displacing the "blank" specimen holder against the pre-positioned stop. With the chamber door closed and inlet vent opened, adjust the compressed air supply to the radiometer cooler to maintain its body temperature at 200 ± 5°F (93° ± 3°C). Adjust the autotransformer setting so as to obtain the calibrated millivolt output of the radiometer corresponding to a steady-state irradiance of 2.2 ± 0.04 Btu/s-ft² (2.5 ± 0.05 W/cm²) averaged over the central 1.5-in. (38.1-mm) diameter area. Use the recorder or meter described in 7.1.8 to monitor the radiometer output. After the prescribed irradiance level has reached steady-state, remove the radiometer from the chamber and replace with the "blank" specimen holder.

11.6 After the system has reached steady-state conditions, adjust the zero of the meter or recorder, or both. Adjust the amplifier sensitivity to obtain a full-scale reading of the photodetector (100 % transmittance) on the recorder or readout meter. Determine the "dark current" (0 % transmittance) on the

⁸ Bostitch B8. Swingline 888. Acc. Monarch No 1 FT. or similar, have been found satisfactory.

⁹ An ammoniated spray detergent and soft scouring pads have been found effective.

maximum sensitivity range of the readout meter by blocking the light. Adjust the "dark current" reading to zero.

11.7 For nonflaming exposures, remove the multiple flamelet burner. For flaming exposures, position the burner across the lower edge of the specimen as described in 7.1.10. Check the burner distances relative to the "blank" specimen before fuel adjustment and ignition.

11.8 Before positioning the test specimen, flush the chamber with the door and exhaust and inlet vents open for about 2 min, and verify the starting temperature of the chamber, using the procedure described in 11.3.

11.9 Close the exhaust vent and blower. Place the loaded specimen holder on the bar support and push it into position in front of the furnace (with burner in position for flaming exposure) by displacing the "blank" holder. Quickly close the chamber door and simultaneously start the timer or recorder chart drive, or both. Close the inlet vent completely only when the photometer indicates the presence of smoke.

11.10 Record the light transmittance and the corresponding time either as a continuous plot with a multirange recorder or at time intervals no greater than 30 s with a multirange meter readout. Make and note the necessary full-scale range changes in decade steps.

11.10.1 The photometer used with this instrument shall have an accuracy of $\pm 3\%$ or better of the maximum reading on any range. As such, the percentage error of a given reading becomes progressively worse at the lower portion of the scale. Avoid light transmittance on scale readings less than 10 by making the appropriate decade range change.

11.10.2 Some chambers are equipped with a switch that not only incorporates ranges of 100, 10, 1, and 0.1 but also ranges of 30, 3, and 0.3. With such an instrument the greatest accuracy would be achieved in light transmittance readings by making a range change in these intermediate ranges when the light transmittance reading reaches 30 on the 0-to-100 meter scale or 10 on the 0-to-33 scale.

11.11 Observe the increase in chamber pressure with the manometer described in 7.1.9. Use regulator (see A2.8) to maintain the pressure in the range of 4 ± 2 in. (100 ± 50 mm) of water during most of the test. If negative pressure develops after very intense specimen flaming, open the inlet vent slightly to equalize the pressure. As a result of pressure rise, adjust the fuel and air valves during the flaming test to maintain constant flow rate.

11.12 Record any observations pertinent to the burning and smoke generating properties of the material under test, in accordance with 13.1.6 and 13.1.7.

11.13 Continue the test for a period of 3 min after a minimum light transmittance value is reached or after an exposure of 20 min, whichever occurs first.

11.13.1 Optionally, the test shall be permitted to be conducted for periods in excess of 20 min at the request of the test sponsor.

11.14 If transmittance falls below 0.01 %, the chamber window shall be covered with an opaque screen to avoid possible light-scattering effects from room light. Also any supplementary optical filter in the photometer system shall be removed or displaced in order to extend the measuring range.

If the potential exists for extraneous light to reflect into the photometer during removal of the filter, turn the high voltage off or adjust the scale to minimize sensitivity. Replace the filter before exhausting smoke from the chamber.

11.15 Extinguish the burner on flaming exposures and start exhausting the chamber within 1 min after terminating the test (see 11.13 and Note 2). Displace the specimen from the front of the furnace by pushing the "blank" specimen holder with the positioning rod. Continue to exhaust with the inlet vent open until maximum transmittance is reached. Record this transmittance value as the T_c , "clear beam" reading.

Note 2—In some cases the transmittance will increase somewhat and subsequently decrease to the ultimate minimum transmittance.

12. Calculation

12.1 Calculate specific optical density, D_s , at any given time as follows:

$$D_s = G [\log_{10} (100/T) + F]$$

where:

$G = V/AL$,

$V =$ volume of the closed chamber, ft^3 (or m^3),

$A =$ exposed area of the specimen, ft^2 (or m^2),

$L =$ length of the light path through the smoke, ft (or m),

$T =$ percent light transmittance as read from the light-sensing instrument, and

$F =$ depends on the following:

(1) If the movable filter (see 7.1.5.3) is in the light path at the time that T is being measured, $F = 0$, and T is the actual percent transmittance.

(2) If the filter has been moved out of the light path (see 7.1.5.3 and 11.14) at the time that T is being measured, $F =$ the known optical density of the filter (see A.1.1.4), and T is an apparent percent transmittance.

(3) If the optical system is not equipped with a movable filter in accordance with 7.1.5.3, $F = 0$, and T is the actual percent transmittance.

12.1.1 For an instrument constructed in accordance with this standard, corrections for the volume of the furnace assembly and the volume included in the door recess are generally less than 1 %. As such, $G = 132$.

12.1.2 A table for D_s versus actual percent light transmittance is given in Appendix X2. The D_s values above 528 are based on an assumed optical density of 2.00 for the movable filter.

12.2 Calculate the maximum specific optical density, D_m , using the equation in 12.1 with a light transmittance corresponding to the minimum level reached during the test.

12.2.1 Similarly, calculate D_c using the T_c value.

12.2.2 Calculate D_m (corrected) as follows:

$$D_m (\text{corr}) = D_m - D_c$$

12.3 For systems without "dark current" cancellation or "blank adjust" provisions, a correction shall be made for any light transmittance reading, T , approaching the dark current value, T_d . Calculate the corrected light transmittance, T' , as follows:

$$T' = 1 - \frac{1 - T}{1 - T_d} = \frac{T - T_d}{1 - T_d}$$

and is used for the specific optical density calculations described in 12.1 and 12.2.

12.4 Determine t_{D_m} , the time in minutes for the smoke to accumulate to the maximum specific optical density.

12.5 When the test is continued beyond the standard 20-min exposure, make all calculations in accordance with 12.1-12.4 and identify the results as "Extended Exposure."

13. Report

13.1 Report the following information:

13.1.1 Complete description of the material tested including: type, manufacturer, shape, thickness, or other appropriate dimensions, weight or density, coloring, and any other relevant details.

13.1.2 Complete description of the test specimens, including: substrate or core, special preparation, mounting, specimen orientation, and any other relevant details.

13.1.3 Information regarding the test specimen, conditioning procedure and the duration of conditioning.

13.1.4 Number of specimens tested.

13.1.4.1 When nonisotropic materials are not tested for each orientation, information on the data and appropriate criteria used to justify the use of only one orientation shall be included (see 8.2). Such information shall include the source and availability of the data.

13.1.5 Test conditions: type of exposure, the exposure period, and temperature of chamber wall.

13.1.6 Observations of the behavior of the specimen during test exposure, such as delamination, sagging, shrinkage, melt-

ing, collapse, and any other relevant details, including the time of such occurrence. The time of any change in exposure mode shall be noted.

13.1.7 Observations of the smoke-generating properties of the specimens during exposure, such as color of the smoke, nature of the settled particulate matter, etc.

13.1.8 A tabulation or curve of time versus either percent transmittance or D_x (rounded to two significant figures) for each run of the three test specimens.

13.1.9 Test results rounded to two significant figures as described in Section 12 including the average and range on each set of specimens for D_m with time of occurrence, and $D_m(\text{corr})$.

NOTE 3—Prior to the adoption of this test method, it was customary to report the maximum smoke accumulated as $D_m(\text{corr})$, and for that reason it has been included as a part of the test report. Subsequently, a statistical analysis of the round-robin data upon which the precision statement is based, showed that the D_m values were more uniform. Therefore, it is required that both D_m and $D_m(\text{corr})$ be reported.

14. Precision and Bias

14.1 Precision:

14.1.1 Tables 1 and 2 are calculated from the results obtained when 25 materials were tested by 20 laboratories in a round-robin study conducted by ASTM Subcommittee E05.02, following a prior draft version of this method. That study indicated several sections of the test procedure that required additional description, and this version has been revised accordingly. It is reasonable to expect that this version of the method will provide better precision than that tabulated.

TABLE 1 Precision Statement for D_m —Flaming^a

Material	Coefficients of Variation, %		Relative Precision, %	
	Within a Laboratory	Between Laboratories	Within a Laboratory (R_1)	Between Laboratories (R_2)
Hardboard, unfinished, 1/4 in.	21.2	10.7	33.9	45.1
Particleboard, untreated, 3/8 in.	29.7	25.3	47.5	84.7
Lauan hardwood, plywood, unfinished, grade AD, 1/4 in.	25.2	24.5	40.3	78.9
Hemlock, untreated, 3/4 in.	24.8	24.5	39.7	78.6
Hemlock, treated, 3/4 in.	26.2	11.9	41.9	53.2
Red oak, 3/4 in.	27.2	39.3	44.4	117.7
Acoustical ceiling tile, untreated, 1/2 in.	22.3	24.4	35.7	78.5
Nonacoustical ceiling tile, untreated, 1/2 in.	26.9	28.8	43.1	90.8
Standard gypsum board, 1/2 in.	18.0	35.6	28.8	102.9
1/2 in. high-pressure standard decorative laminate, urea glue, on 1/4 in. untreated particleboard	17.2	23.1	27.5	69.7
1/2 in. high-pressure, fire retardant decorative laminate, resorcinol adhesive, on 3/4 in. treated particleboard	9.3	14.5	14.8	42.8
Linoleum	9.5	14.6	15.2	43.2
Wool plush carpet	15.4	10.2	24.7	37.4
Polyester twist carpet	19.8	13.5	31.4	48.9
Nylon twist carpet	3.6	10.9	5.7	30.8
Acrylic carpet	7.5	14.1	12.0	41.0
Fiber glass-reinforced brominated polyester sheet	11.8	9.2	18.9	31.7
Poly(vinyl chloride) flooring	14.3	9.1	22.9	34.1
Poly(methyl methacrylate) sheet	16.9	24.1	27.0	72.0
Flexible polyurethane foam, high resiliency, 1/2 in.	29.6	23.6	47.3	80.7
Rigid polyisocyanurate foam, 1/2 in.	6.2	13.4	10.0	38.4
NBS SRM 1007a ^b	6.5	7.6	10.4	23.0

^a Precision statements for polystyrene sheet and fiber glass-reinforced polyester sheet are not given because the D_m values fell outside the range of the instrument.

^b The average D_m value obtained by 20 laboratories testing 3 samples each (60 samples) was 433.

TABLE 2 Precision Statement for D_m —Nonflaming^A

Material	Coefficients of Variation, %		Relative Precision, %	
	Within a Laboratory	Between Laboratories	Within a Laboratory (R_1)	Between Laboratories (R_2)
Lauan hardwood plywood, unfinished, grade AD, 1/4-in.	5.6	10.7	8.9	30.9
Untreated hemlock, 3/4-in.	16.4	14.1	26.2	47.1
Hemlock, treated, 3/4-in.	32.1	11.4	51.4	60.4
Red oak, 3/4-in.	7.7	21.1	12.3	59.7
Acoustical ceiling tile, untreated, 1/2-in.	9.3	9.9	14.9	31.3
Nonacoustical ceiling tile, untreated, 1/2-in.	13.3	14.6	21.4	45.7
Standard gypsum board, 1/2-in.	5.6	12.3	8.9	35.3
1/2-in. high-pressure standard decorative laminate, urea glue, on 3/4-in. untreated particleboard	6.2	11.9	9.9	34.5
1/2-in. high-pressure fire-retardant decorative laminate, resorcinol adhesive, on 3/4-in. treated particleboard	20.1	30.2	32.1	89.7
Wool plush carpet	9.1	14.0	14.6	41.6
Polyester twist carpet	9.6	8.8	15.4	28.8
Nylon twist carpet	8.3	14.0	13.8	41.1
Acrylic carpet	6.8	9.4	10.9	28.9
Fiber glass-reinforced brominated polyester sheet	4.6	10.0	7.4	28.6
Poly(vinyl chloride) flooring	6.3	13.8	10.0	39.5
Polystyrene sheet	15.0	12.8	24.1	42.8
Poly(methyl methacrylate) sheet	24.0	29.9	38.5	91.5
Fiber glass-reinforced polyester sheet	7.1	5.7	11.3	19.4
Flexible polyurethane foam, high resiliency, 1/2-in.	10.1	10.6	16.2	33.6
Rigid polyisocyanurate foam, 1/2-in.	11.9	18.9	19.0	55.8
NBS SRM 1006 ^B	3.1	5.5	5.0	16.0

^A Precision statements for hardboard, unfinished, 1/4-in.; particleboard, untreated, 3/4-in.; and linoleum are not given because the D_m values fell outside the range of the instrument.

^B The average D_m value obtained by 20 laboratories testing 3 samples each (60 samples) was 164.

14.1.2 The precision statements in these tables are expressed as a percentage of the average D_m of each material and are based on only the validated results (see Section 3) from the three replicates submitted to each laboratory.

14.1.3 *Coefficient of Variation*—The ratio of either the “within laboratory” or “between laboratories” standard deviation to the overall average D_m value for the material, expressed as a percent.

14.1.4 *Relative Precision*:

14.1.4.1 *Repeatability, R_1* —The critical difference within which two averages of three specimens each, obtained on the same material by a single operator using the same instrument, can be expected to lie 95 % of the time because of random variation within a laboratory.

14.1.4.2 *Reproducibility, R_2* —The critical difference within which two averages of three specimens each, obtained by two different operators, using different instruments in different laboratories, can be expected to lie 95 % of the time because of the random variations within and between laboratories.

14.2 *Bias*—The bias is unknown because the value of specific optical density obtained in this procedure is defined only in terms of this test method.

15. Keywords

15.1 fire; fire-test response standard; smoke; smoke chamber; smoke density; smoke obscuration; solids; specific optical density

ANNEXES

(Mandatory Information)

A1. CALIBRATION OF TEST EQUIPMENT

A1.1 Photometric System

A1.1.1 A properly used photometer of the type described in this document is an inherently linear device provided that linear electronic measuring and recording equipment has been used. The linearity of absorption measurements is not dependent upon critical beam collimation; however, collimation of

the optical beam may be of importance in cases where light scatter takes place, as often occurs in smoke aerosols. Because of this, the following instructions are included for use in cases where the photometer beam needs to be realigned following replacement of the light source or some accidental misalignment.

A1.1.2 Alignment:

A1.1.2.1 Prepare an opaque templet about 4½ in. (115 mm) in diameter with a centered 2-in. (51-mm) diameter drawn circle.

to that corresponding to human vision. This is defined by the operating condition of the lamp source and the spectral sensitivity of the photodetector. Since no precise control is maintained over the size of this spectral band, it would be

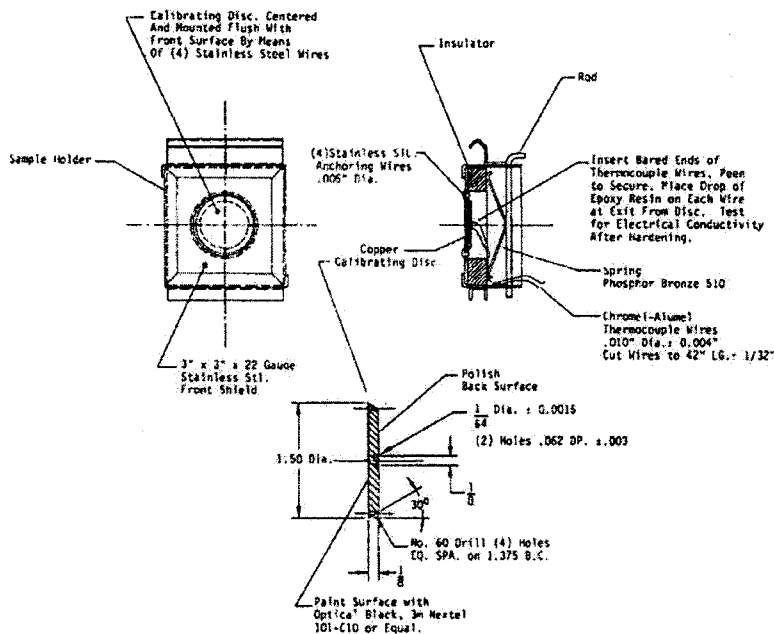


FIG. A1.1 Copper Disk Calorimeter

A1.1.2.2 Attach the templet with transparent tape to, and centered on, the upper optical window. With the optical system in its normal operational mode, observe the projected image on the templet. A properly aligned beam will completely fill the 2-in. (51-mm) circle with some spill-over. Because of the filament, the pattern will not be a perfect circle. If the pattern is too large or too small, the lower lens will require adjustment. Remove the cover from the light source enclosure. If the pattern is not centered, it will require repositioning of the light source or slight readjustment of the lens mount in its track. One way to optimize the lens position is by slight adjustment until the maximum photometer reading is obtained, whereupon it is locked. Replace the enclosure cover, making sure that all screws have been tightly seated.

A1.1.2.3 Switch off the photometer and remove the cover from the roof-mounted optical enclosure. Remove the compensating filter holder from the lens mount and observe the converging beam of light. A properly focused and aligned beam will form a small intense spot at the disk aperture of the photomultiplier housing projecting into the roof of the enclosure. If the beam is misaligned or not properly focused, loosen the lens mount screws very slightly and carefully refocus. Tighten the screws and recheck the light spot. Remount the compensating filter holder into the lens mount and replace the enclosure cover. Replace all screws to prevent light leaks.

A1.1.3 Linearity Check—The photometer used with this instrument shall have an accuracy of ±3 % of the maximum reading on any range. It involves a spectral band quite similar

necessary, if accurate calibration were to be attempted, to make use of filters with constant transmission over a spectral band of at least 350 to 750 nm. Such filters are not readily available. Because of this and the inherent linearity of a properly constructed photometer and measuring circuit, it is not recommended that the test method user attempt precise calibration of the instrument over its operating range. The following rough calibration procedure is, however, recommended as a means to ensure that no gross failure of the photometric measuring system has occurred:

A1.1.3.1 Complete alignment as in A1.1.2.

A1.1.3.2 With the photometer beam blocked, determine that the instrument shows zero transmission on all the normal photometer ranges without removal of the range extension filter from the photometer head.

A1.1.3.3 Measure the transmission of a neutral density filter of nominal optical density of 3.0 which has been previously calibrated in another smoke density photometer. The two transmission measurements shall agree within 5 % of the mean of the two measurements. Failing such agreement, investigate to determine the reason for the discrepancy.

A1.1.4 Range Extension Filter—If equipped with the normal commercial microphotometer with incorporated dark current or blank adjust features, the system is only able to measure to 0.01 % transmittance, equivalent to a specific optical density of 528. To permit extension beyond this range, the commercial system is equipped with a glass ND2 filter in the shutter assembly. Determine the precise transmission of this filter as

follows: With the optical system adjusted as stated in 11.5 and leaving the filter in the optical path, allow the chamber to stabilize at the operating temperature (35°C). Place over the lower window a white cloth or tissue sufficiently thick so as to give a "midscale" reading when the photometer range switch

A1.2.3 Allow the furnace and radiometer output and body temperature to equilibrate until a steady-state, millivolt-output of the radiometer is obtained.

A1.2.4 Remove the radiometer and place a cool rate-of-heat rise copper disk calorimeter (Fig. A1.1) promptly in front of the

TABLE A1.1 Correction Factors for Range Extension Filter ND2 Neutral Density Filter Removal Correction Factors^a

Meter indication, %T	Correction factor, C _i	Optical density of neutral density filter, log P ₀ /P=D	Meter indication, %T	Correction factor, C _i	Optical density of neutral density filter, log P ₀ /P=D
31	-27.4	1.79	51	+1.1	2.01
32	-25.6	1.81	52	+2.2	2.02
33	-23.8	1.82	53	+3.3	2.025
34	-22.1	1.83	54	+4.4	2.03
35	-20.4	1.845	55	+5.5	2.04
36	-18.8	1.86	56	+6.5	2.05
37	-17.3	1.87	57	+7.5	2.06
38	-15.7	1.88	58	+8.5	2.064
39	-14.2	1.89	59	+9.5	2.07
40	-12.8	1.90	60	+10.5	2.08
41	-11.4	1.91	61	+11.4	2.086
42	-10.0	1.92	62	+12.3	2.09
43	-8.6	1.93	63	+13.2	2.10
44	-7.3	1.94	64	+14.2	2.107
45	-6.0	1.95	65	+15.0	2.114
46	-4.8	1.96	66	+15.9	2.12
47	-3.5	1.97	67	+16.8	2.13
48	-2.3	1.98	68	+17.6	2.135
49	-1.2	1.99	69	+18.5	2.14
50	0.0	2.00	70	+19.3	2.146

^aCorrections are to be applied to the D_s values equivalent to the 0.01 to 0.001 %T and 0.001 to 0.00001 %T values only.

is set to the "1-scale." Adjust the micrometer knob to give an exact mid-scale reading (0.5 % transmittance). Rotate the range switch back to the "100-scale" and move the range extension filter out of the optical path. Observe the meter reading. If the meter reading is 50 % T, the value of the filter is exactly optical density 2.0 and the preprinted conversion tables, Appendix X2, are suitable for direct use. If the meter indication is high, the filter value is less than optical density 2.0, and if the meter indication falls below 50 % T the optical density exceeds 2.0. Determine the correction to be applied to the range extension D_s values in Appendix X2 from Table A1.1.

A1.2 Radiometer

A1.2.1 Calibrate the radiometer by comparing its voltage output when exposed to heat from the furnace to that of a copper disk calorimeter (see Fig. A1.1) (primary standard) when the latter is exposed to the same heat flux. Calibrate at four furnace settings, two above and two below the nominal 2.5-W/cm² set point of the test method. From this, draw a graph, plotting the heat flux received by the radiometer against its voltage output. The procedure and calculations are as follows:

A1.2.2 With the furnace operating at a voltage setting between 90 and 95 V place the radiometer on the support rods so that it is positioned and oriented exactly as a test specimen relative to the furnace. Adjust the air flow to the radiometer cooler to maintain the body temperature of the radiometer at 200 ± 5°F (93 ± 3°C).

furnace in the same position as in A1.2.2. Immediately thereafter, obtain a short (5 to 15-s) record of the temperature rise of the disk. Determine this temperature rise of the calorimeter by measuring the electrical output of the thermocouple attached to the back of the disk, employing a recording potentiometer operating at a fast chart speed (1 in./s; 25 mm/s). Remove the calorimeter and allow it to cool back to room temperature.

A1.2.5 Adjust the furnace voltage to three additional settings and repeat steps A1.2.2-A1.2.4 for each setting.

A1.2.6 Choose the furnace settings so that the output of the radiometer, expressed in W/cm² of radiant heat received, brackets the value 2.50 W/cm².

A1.2.7 Relate the output of the radiometer, expressed in millivolts, to the linear portion of the temperature rise of the copper disk, for each furnace setting by the following calculations:

- Q_r = radiant heat received by radiometer, Units
- = radiant heat received by copper disk, W/cm²
- = $G (d^2/dt) = (G/k) \times [d(mV)/dt]$
- where:
- $\frac{d^2}{dt^2}$ = rate of temperature rise of copper disk, °C-s⁻¹
- $\frac{d(mV)}{dt}$ = slope of thermocouple millivolt output on recording potentiometer, mV-s⁻¹
- k = thermocouple conversion constant
- = 0.040 mV × °C⁻¹ for Chromel-Alumel between 20°C and 40°C, and mV-°C⁻¹
- = constant for the particular disk used = Kmc/A_r , g
- where:
- K = conversion factor = 4.184, W-s-cal⁻¹
- m = mass of copper disk, uncoated, g
- c = specific heat of copper = 0.0927, cal-g⁻¹-°C
- A_r = net area of exposed (blackened) face of copper disk cm²
- = $A_g - nA_r$

A_g = gross area of exposed face, cm^2
 n = number of holes for supporting wires.
 A_h = area of each hole, and cm^2
 a = radiation absorption of black coating on face of disk¹⁰

weighing 29.78 g and having a net area of 11.37 cm^2 .

A1.2.7.1 The use of this copper disk calorimeter in calibrating a radiometer is illustrated by the following example:

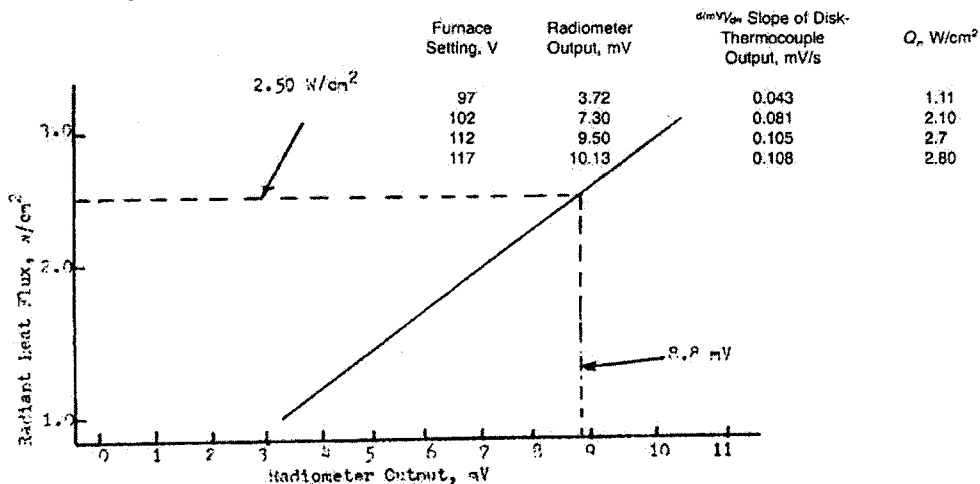


FIG. A1.2 Example—Calibration of Radiometer

NOTE A1.1—As an example of the procedure proposed, it is possible to simplify the equation for the radiant heat absorbed by a particular copper disk, as follows:

Assume, as an example:

m = 29.78 g
 A_g = 11.40 cm^2
 n = 4
 A_h = 0.008 cm^2

Then:

A_n = 11.37 cm^2
 C = 0.0927 $\text{cal}\cdot\text{g}^{-1}\cdot^\circ\text{C}^{-1}$
 K = 4.184 $\text{cal}\cdot\text{g}^{-1}\cdot^\circ\text{C}^{-1}$
 k = 0.040 $\text{mV}\cdot^\circ\text{C}^{-1}$
 a = 0.98

from which

$$Q_r = \frac{4.184 \times 29.78 \times 0.0927}{11.37 \times 0.98 \times 0.04} \times \frac{d(mV)}{d\theta}$$

$$= 25.91 \frac{d(mV)}{d\theta}$$

NOTE A1.2—The above is an example only and applies to a disk

From the above, a graph is obtained by drawing a best straight line through the plotted points and selecting the indicated output intersecting the line at 2.5 W/cm² (see Fig. A1.2). From this graph, the output of the radiometer corresponding to a radiant heat flux of 2.50 W/cm² is obtained; in this case the value is 8.8 mV.

A1.2.8 Under normal continuous use conditions, the radiometer shall be calibrated at least once every three months. Annual recalibrations shall be required in all cases.

A1.2.9 The blackened face of the radiometer shall be inspected frequently. In case the coating is blistered, cracked, discolored, or broken, the coating shall be removed, the face of the radiometer cleaned, and a new coating applied. In this case, the recoated radiometer shall be recalibrated before being used.

A1.2.10 The copper disk standard shall be carefully handled when in use, and protected from surface contamination and mechanical abuse when stored. If the blackened face shows alterations as in A1.2.9 the coating shall be removed and the face cleaned. The disk shall then be reweighed and recoated and any appropriate corrections made in the calibration constant, G , before it is used again.

¹⁰ Nextel velvet 101-C10 provides a radiation absorption characteristic (a) of 0.98. Nextel velvet 101-C10 and its replacement, Solar Absorber Coating ECP-2200, are no longer manufactured by 3M Company. Nextel is a registered trademark of the 3M Company.

A2. CONSTRUCTION DETAILS

A2.1 Radiant Heat Furnace

A2.1.1 The furnace shown in Fig. 2 has been found to be suitable. The dimensions that are shown in Fig. 2 and the components to which they refer are critical. Other portions of the design are optional. The heating element consists of a coiled wire or other suitable electrical heating element capable of dissipating about 525 W, mounted vertically in a horizontal ceramic tube 3 in. (76.2 mm) in inside diameter by $3\frac{3}{8}$ in. (85.7 mm) in outside diameter by $1\frac{5}{8}$ in. (41.3 mm) long. The tube is bored out at one end to $3\frac{1}{2}$ in. (77.0 mm) inside diameter and to a depth of $\frac{3}{8}$ in. (15.9 mm) to accommodate the heating element. A $\frac{1}{16}$ -in. (1.6-mm) insulation paper gasket and two stainless steel reflectors are mounted behind the heating element. A $\frac{3}{8}$ -in. (9.5-mm) insulation millboard disk, provided with ventilation and lead wire holes, shall be positioned behind the heating element and used to center the assembly with respect to the front $\frac{3}{8}$ -in. (9.5-mm) insulation millboard ring by means of a 6-32 stainless steel screw. The adjustment nuts on the end of the centering screw shall provide proper spacing of the furnace components. The cavities adjacent to the heating element assembly shall be packed with glass wool. The furnace assembly shall be housed in a 4-in. (102-mm) outside diameter by 0.083-in. (2.1-mm) wall by $4\frac{1}{8}$ -in. (105-mm) long stainless steel tube. Two additional $\frac{3}{8}$ -in. (9.5-mm) insulation board spacing rings and a rear cover of $\frac{3}{8}$ -in. (9.5-mm) insulation board shall complete the furnace. The furnace shall be located centrally along the long axis of the chamber with the opening facing toward and about 12 in. (305 mm) from the right wall. The centerline of the furnace shall be about $7\frac{3}{4}$ in. (195 mm) above the chamber floor.

A2.2 Specimen Holder

A2.2.1 The specimen holder shall conform in shape and dimension to Fig. 3 and be fabricated by bending and brazing (or spot welding) 0.025-in. (0.6-mm) thick stainless steel sheet to provide a $1\frac{1}{2}$ -in. (38.1-mm) depth, and to expose a $2\frac{9}{16}$ in. (65.1 mm) by 65.1-mm specimen area. As described in 7.1.3, the holder shall have top and bottom guides to permit accurate centering of the exposed specimen area in relation to the furnace opening. A3 by 3-in. (76.2 by 76.2-mm) sheet of $\frac{1}{2}$ -in. (12.7-mm) inorganic insulation millboard, having a nominal density of 50 ± 10 lb/ft³ (800 ± 160 kg/m³) shall be used to back the specimen. A spring bent from 0.010 in. (approximately 0.25-mm) thick phosphorbronze sheet shall be used with a steel retaining rod to securely hold the specimen and millboard backing in position during testing.

A2.3 Support of Furnace and Specimen Holder

A2.3.1 The framework as shown in Fig. 4 shall have welded to it a 5-in. (127-mm) outside diameter, $\frac{1}{4}$ -in. (6.4-mm) wall, 2-in. (50.8-mm) long horizontally oriented steel tube to support the radiant heat furnace described in 7.1.2. This support tube shall have provision to accurately align the furnace opening so that it is $1\frac{1}{2} \pm \frac{1}{32}$ in. (38.1 ± 0.8 mm) away from, parallel to, and centered with respect to the exposed specimen area.

A2.3.2 Adjustment screws shall be provided to align the furnace with reference to the specimen.

A2.3.3 The framework shall have two $\frac{3}{8}$ -in. (9.5-mm) diameter transverse rods of stainless steel to accept the guides of the specimen holder described in 7.1.3. The rods shall support the holder so that the exposed specimen area is parallel to the furnace opening. Spacing stops shall be mounted at both ends of each rod to permit quick and accurate lateral positioning of the specimen holder.

A2.4 Photometric System

A2.4.1 The photometric system shall consist of a light source and photosensitive element as defined in 7.1.5. The system shall be as shown in Figs. 5 and 6. The window in the chamber floor through which the light beam passes shall be provided with a ring-type electric heater mounted on the underside of the window out of the light path. The heater maintains the minimum window temperature at 125°F (52°C) on the inner surface of the window to minimize smoke condensation. The collimated beam inside the chamber shall have a path length of $36 \pm \frac{1}{8}$ in. (914 ± 3 mm) and a sensing cross section of $1\frac{1}{2} \pm \frac{1}{8}$ -in. (38 ± 3 -mm) diameter (see Annex A1). A typical photomultiplier photometer system will require a high-voltage d-c power supply and a neutral density filter of sufficient optical density to produce a convenient signal level for the indicator or recorder. The photometer system used shall be capable of permitting the recording of reliable optical densities of at least 6.0, corresponding to transmittance values of 0.0001 % of the incident light (see Appendix X2).

A2.4.1.1 The two optical platforms and their housings shall be kept in alignment with three metal rods, $\frac{1}{2}$ in. (12.7 mm) in diameter, fastened securely into $\frac{5}{16}$ -in. (7.9-mm) thick externally mounted top and bottom plates and symmetrically arranged about the collimated light beam.

A2.5 Radiometer

A2.5.1 The 200°F (98°C) body temperature of the radiometer shall be monitored with a 100 to 200°F (38 to 100°C) thermometer located as shown in Fig. 7 in a $\frac{1}{2}$ by $\frac{1}{2}$ by $1\frac{1}{2}$ -in. (12.7 by 12.7 by 38.1-mm) long brass or copper well drilled to accept the thermometer with a close fit. The use of silicone grease is a way to enhance the probability of providing good thermal contact. The circular receiving surface of the radiometer shall be spraycoated with an infrared-absorbing black paint. The radiometer shall be calibrated calorimetrically in accordance with the procedure summarized in A1.2.

A2.6 Chamber Wall Thermocouple

A2.6.1 A thermocouple suitable for measuring a temperature of 35°C shall be mounted with its junction secured to the geometric center of the inner rear wall panel of the chamber using an electrical insulating disk cover and epoxy cement.

A2.7 Burner

A2.7.1 The multiple burner shall have six tubes with construction details as shown in Fig. 3 (Note A2.1). The six tubes

shall be made from 1/8-in. (3.2-mm) outside diameter by 0.031-in (0.8-mm) wall stainless steel tubing. All tubes shall be swaged at the tip to reduce the opening diameter to 0.055 in. (1.4 mm). The manifold section of the burner shall consist of 1/4-in. (6.4-mm) outside diameter by 0.035-in. (0.9-mm) wall stainless steel tubing. The other end of the manifold is attached to a fitting in the chamber floor.

NOTE A2.1—The two outer tubes shall be directed normal to the surface of the specimen. The two inner tubes shall be directed at an angle of 45°

downward. The two intermediate tubes shall be directed vertically downward into the trough of the specimen holder.

A2.8 Chamber Pressure Regulator

A2.8.1 A suitable pressure regulator consists of an open, water-filled bottle and a length of flexible tubing, one end of which is connected to a sampling port on the top of the chamber. The other end of the tubing is inserted 4 in. (100 mm) below the water surface. The bottle shall be located at or below the floor level of the chamber to avoid back-siphoning.

APPENDICES

(Nonmandatory Information)

X1. ADDITIONAL CALCULATIONS

X1.1 The smoke chamber test results in a curve of specific optical density versus time. The maximum specific optical density, D_m , represents total smoke accumulation. Additional information that may be of value might include:

- R_m — maximum rate of increase in specific optical density per minute, measured over any 2-min period, or 2 min from the start of the test.
- t_{10} — time to reach $D_s = 16$ ($T = 75\%$), or other smoke level. This is a simple measurement of initial smoke generation.
- SOI — an abbreviation for the smoke obscuration index and incorporates the effects of total smoke, generation rate, and time to reach $D_s = 16$. It is calculated as follows:

$$SOI = \frac{(D_m)^2}{2000 t_{16}} \left(\frac{1}{t_{0.3} - t_{0.1}} + \frac{1}{t_{0.5} - t_{0.3}} + \frac{1}{t_{0.7} - t_{0.5}} + \frac{1}{t_{0.9} - t_{0.7}} \right)$$

where $t_{0.1}$, $t_{0.3}$, indicate the time in minutes at which the smoke accumulation reaches 10, 30, etc., % respectively, of the maximum density D_m .

X2. TABULAR CONVERSION OF PERCENT TRANSMITTANCE TO SPECIFIC OPTICAL DENSITY WHEN G = 132.

PARAMETERS AND TRANSMITTANCE RANGE	%T	SPECIFIC OPTICAL DENSITY (D _s)									
		0	1	2	3	4	5	6	7	8	9
MULTIPLIER: 100 with ND-2 Filter	90	6	5	5	4	4	3	2	2	1	1
	80	13	12	11	11	10	9	9	8	7	7
	70	20	20	19	18	17	16	16	15	14	14
	60	29	28	27	26	26	25	24	23	22	21
	50	40	39	37	36	35	34	33	32	31	30
	40	53	51	50	48	47	46	45	43	42	41
100 to 10 %T	30	69	67	65	64	62	60	59	57	55	54
	20	92	89	87	84	82	79	77	75	73	71
	10	132	127	122	117	113	109	105	102	98	95
	90 x 10 ⁻¹	138	137	137	136	136	135	134	134	133	133
	80	145	144	143	143	142	141	141	140	139	139
	70	152	152	151	150	149	148	148	147	146	146
10 to 1 %T	60	161	160	159	158	158	157	156	155	154	153
	50	172	171	169	168	167	166	165	164	163	162
	40	185	183	182	180	179	178	177	175	174	173
	30	201	199	197	196	194	192	191	189	187	186
	20	224	221	219	216	214	211	209	207	205	203
	10	264	259	254	249	245	241	237	234	230	227
MULTIPLIER: 1 with ND-2 Filter	90 x 10 ⁻²	270	269	269	268	268	267	266	266	265	265
	80	277	276	275	275	274	273	273	272	271	271
	70	284	284	283	282	281	280	280	279	278	278
	60	293	292	291	290	290	289	288	287	286	285
	50	304	303	301	300	299	298	297	296	295	294
	40	317	315	314	312	311	310	309	307	306	305
1 to 0.1 %T	30	333	331	329	328	326	324	323	321	319	318
	20	358	353	351	348	346	343	341	339	337	335
	10	396	391	386	381	377	373	369	366	362	359
	90 x 10 ⁻³	402	401	401	400	400	399	398	398	397	397
	80	409	408	407	407	406	405	405	404	403	403
	70	416	416	415	414	413	412	412	411	410	410
0.1 to 0.01 %T	60	425	424	423	422	422	421	420	419	418	417
	50	436	435	433	432	431	430	429	428	427	426
	40	449	447	446	444	443	442	441	439	438	437
	30	465	463	461	460	458	456	455	453	451	450
	20	488	485	483	480	478	475	473	471	469	467
	10	528	523	518	513	509	505	501	498	494	491
MULTIPLIER: 1 without ND-2 Filter	90 x 10 ⁻⁴	534	533	533	532	532	531	530	530	529	529
	80	541	540	539	539	538	537	537	536	535	535
	70	548	548	547	546	545	544	544	543	542	542
	60	557	556	555	554	554	553	552	551	550	549
	50	568	567	565	564	563	562	561	560	559	558
	40	581	579	578	576	575	574	573	571	570	569
0.01 to 0.001 %T	30	597	595	593	592	590	588	587	585	583	582
	20	620	617	615	612	610	607	605	603	601	600
	10	660	655	650	645	641	637	633	630	626	623
	90 x 10 ⁻⁵	666	665	665	664	664	663	662	662	661	661
	80	673	672	671	671	670	669	669	668	667	667
	70	680	680	679	678	677	676	676	675	674	674
0.001 to 0.00001 %T	60	689	688	687	686	686	685	684	683	682	681
	50	700	699	697	696	695	694	693	692	691	690
	40	713	711	710	708	707	706	705	703	702	701
	30	729	727	725	724	722	720	719	717	715	714
	20	752	749	747	744	742	739	737	735	733	731
	10	792	787	782	777	773	769	765	762	758	755
00	--	924	885	861	845	832	821	812	805	798	

X3. SUGGESTED SMOKE DENSITY CHAMBER REPORT FORM

Sample Description _____
 Test No. _____ Operator _____ Date _____

Time, min	%T	D_m	Time, min	%T	D_m	Time, min	%T	D_m
0.5			7.5			14.5		
1.0			8.0			15.0		
1.5			8.5			15.5		
2.0			9.0			16.0		
2.5			9.5			16.5		
3.0			10.0			17.0		
3.5			10.5			17.5		
4.0			11.0			18.0		
4.5			11.5			18.5		
5.0			12.0			19.0		
5.5			12.5			19.5		
6.0			13.0			20.0		
6.5			13.5					
7.0			14.0					

Operating Conditions:
 Radiometer Reading _____ mV. @ _____ W/cm²(date & time)
 Furnace Voltage _____ Test Mode: _____ Pyrolysis: _____ w/Flaming: _____
 Flowmeter Settings: Propane @ 50 cm³/min _____ Air @ 500 cm³/min _____
 Chamber: Temperature _____ Pressure _____ in. H₂O
 Chamber Surface Conditions _____

Sample:
 Manufacturer, etc. _____
 Preconditioning: Oven @ _____ °C _____ h Conditioner @ _____ °C _____ RH _____ h
 Thickness _____ mm. Density _____ g/cm³
 Weight: Initial _____ g Final _____ g Wt. Loss _____ g _____ %

Test Results:
 Minimum Transmittance _____ % Maximum D_m _____ Time to Max D_m _____ min
 Clear Beam Reading _____ % T _____ D_m (corr) _____

Optional Presentation:
 Max Rate of D_p /min _____ Time to reach D_p16 _____ min

Remarks: _____

X4. COMMENTARY

X4.1 Introduction

X4.1.1 The smoke density chamber test was developed at the National Bureau of Standards and was first described in an ASTM research symposium in 1967 (2). Since that time, there have been numerous publications reporting on its application and on studies of the correlation of results of interlaboratory tests through its use (3-9).

X4.1.2 The method is somewhat like the box type test developed by Rohm and Haas (see Test Method D 2843 and Ref (10)). However, it provides certain modifications in the nature of specimen exposure and the capability for quantitative measurement of the smoke produced. Advantages provided by use of this test method include: (1) the smoke collection chamber is essentially sealed so all smoke produced during a test is retained; (2) only one surface of a test specimen is exposed to fire or radiant heating, thus providing a measure of effectiveness of surface treatment assisting in control of smoke release; (3) a vertical photometer is used as a means for avoiding measurement errors resulting from smoke stratification; (4) provision is included for reporting the result of smoke measurements in terms of specific optical density, which is a measurement of the amount of smoke produced and hence is useful for comparing one material against another.

X4.1.3 Measurements made with the test relate to light transmission through smoke. No means are provided for predicting the effect of eye irritants in further limiting visual range. Limited information suggests that eye irritants might further reduce vision by 50 to 95 %.

X4.2 Features of Test Method

X4.2.1 Two exposure conditions are simulated by the test: (1) radiant heating in the absence of ignition and (2) an open

flaming combustion of the specimen in the presence of supporting radiation. These two conditions were selected as representative of two types of fire involvement of a product. The irradiance level of 2.5 W/cm² was selected as the highest for which most celluloseics would pyrolyze without selfignition. This irradiance level is much lower than that which would exist in a compartment after flash-over. It more nearly simulates conditions in the initial stages of a fire.

X4.2.1.1 The basis of selection of a specimen irradiance level of 2.5 W/cm² was discussed in X4.2.1. A further comment on the uniformity of irradiance across the specimen surface seems desirable. From a scientific viewpoint, it would be desirable to have constant irradiance over all portions of the specimen. From a practical point of view, this was not feasible because size and heat input of the furnace would have to be greatly increased. It was considered, therefore, more practical to accept a modest nonuniformity of irradiance across the surface of the specimen. This is not defined in terms of radiance units, but rather by specifying the dimensions of the furnace geometry and the specimen spacing. Thus, radiant configuration geometry was selected as a means of specifying the variability of surface irradiance. The average irradiance specified in the test method is that measured by the radiometer described in the standard, an instrument sensitive only to the 1/2-in. diameter central area of the specimen holder.

X4.2.1.2 Fig. X4.1 shows the result of one survey of irradiance across the specimen diagonal. This suggests that the overall average effective flux level during nonflaming pyrolysis is probably about 2.3 W/cm². While this degree of nonuniformity is short of technical perfection, it is accepted as being a practical compromise, considering the likely use to which the test method might be applied.

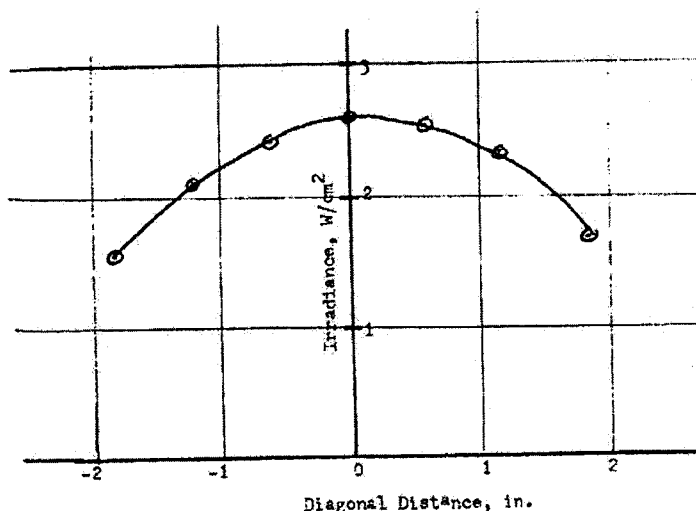


FIG. X4.1 Diagonal Survey of Irradiance at Specimen During Operation at Nominal 2.5 W/cm²

X4.2.2 The primary measurement made during the conduct of the test is the amount of light transmitted as a fraction or percentage of the initial light transmitted by the optical system. The minimum % light transmitted value is, in turn, used to calculate, in accordance with 12.1 of the test method, the maximum specific optical density, D_m , value. There is considerable advantage to using specific optical density as a value by which to evaluate results as compared to using percent light transmittance.

X4.2.2.1 The use of this unit of smoke measurement is based on Bouguer's law of light attenuation which is expressed as follows:

$$T = T_0 e^{-\sigma L}$$

where:

- T = % flux transmittance,
- T_0 = 100, the initial transmitted flux,
- σ = attenuation coefficient, and
- L = length of the optical path.

For a monodispersed aerosol, σ is found to be proportional to the product of size and number of particles. Defining $\log(100/T)$ as being the optical density, d , it can then be developed that:

$$d = \log(100/T) = (\sigma T/2.303)$$

X4.2.2.2 While the smoke produced from fire usually does not meet the requirement of a monodispersed aerosol, it has been found to behave in a photometric manner such that, for engineering purposes, optical density may be considered to be roughly proportional to the smoke particulates produced. The measurement unit, specific optical density, D_s , has been introduced to provide a conveniently factored rating scale as follows:

$$D_s = (V/AL)d = (V/AL) \log(100/T) \text{ where } (V/AL) = 132$$

Previous draft versions of this test method have proposed that, in the situation that the smoke produced exceeds the measurement capability of the apparatus, or if only small specimens were available, specimens less than standard size could be tested and the results extrapolated to the standard specimen size. This procedure should not be used for several reasons, one of which involves the nonuniformity of irradiance and pilot flame exposure.

X4.2.2.3 Certain other test methods report smoke simply in terms of light transmission. The problem of such a procedure is that one not familiar with the characteristics of smoke aerosols might assume that the percent light transmittance is a reciprocal, linear function of the quantity of smoke produced. That is, making the assumption that as the quantity of smoke produced is doubled, the percent light transmittance is cut in half. This is incorrect.

X4.2.3 The concept of specific optical density, while old in terms of chemical photometric practice, was first introduced for measuring smoke as part of the smoke density chamber test method. It is based on Bouguer's law and permits reporting smoke development in terms that recognize the area of specimen involved, the volume of the box, and the optical path length of the photometer. Specific optical density is without dimension, but its value must be recognized as relating to the

specimen only in the thickness tested. In theory, it has the unique advantage of providing a basis for estimating the smoke optical density or lightobscuring properties of smoke that can be developed by the same product in other fire-involved areas, different light paths, in another enclosure volume, on the assumption of uniform smoke-air mixing and under similar fire exposure conditions (11). At the present time, techniques for making these estimates have not been developed to a practical stage because of (1) variations in types of fire exposure, (2) the rate of involvement of a material in a fire, (3) the ventilation characteristics of the compartment, and (4) the degree of stratification of the accumulated smoke. These are, in most instances, undetermined variables which greatly influence light transmission through smoke resulting from a fire.

X4.3 Factors Influencing the Test

X4.3.1 During development of the test method, many factors were considered that could influence the measurements. Some of the more important of these are mentioned and briefly discussed in the following paragraphs:

X4.3.2 It was observed that, in spite of significant thermal convection mixing, smoke near the top of the cabinet was obviously more dense. This fact was verified by experimental measurements. As a result, it was apparent that a vertical photometer would yield a much more representative measurement of smoke accumulation than would be provided by a horizontal unit at one position in the chamber.

X4.3.3 Experiments showed that the optical density of the accumulated smoke was sensitive to the spacing between the specimen face and the plane of the furnace opening. The experiments seem to suggest that the sensitivity was caused by two effects—close spacing caused more smoke to enter the furnace and become consumed there; on the other hand, it also reduced air circulation past the specimen and thus inhibited open flaming combustion. As a result, the separation called for in A.2.3 of $1\frac{1}{2} \pm \frac{1}{32}$ in. was selected as a fair compromise for the purpose of standardization. If this spacing is not held, a small systematic change should be expected in smoke measurement. Similarly, it is necessary to maintain the specified spacing of $3.0 \pm \frac{1}{32}$ in. between the heater face and the specimen surface.

X4.3.4 The use of aluminum foil to wrap the back and edges of the specimen was introduced to provide better standardization because it was found that if smoke was allowed to leak out the back and edges of the specimen holder, the various ways this could occur introduced an undesirable variability in the measurements.

X4.3.5 The question of how to assess, in an equitable fashion, the smoke production of thermoplastics has been a vexing one since early development of the test. The decision to use a vertical specimen orientation was based on knowledge that fire behavior and thus smoke production would differ in vertical and horizontal arrangement positions. Since the method was considered most likely to be applied to evaluation of interior wall finished products, the vertical specimen position was selected as most relevant. Obviously, the thermoplastic problem remained. Portions of such materials were found in varying degrees to melt and drip to the floor of the chamber. Thus, the smoke resulting from such materials is less than

would be expected if all the material remained in the flux field. Whether such materials should be penalized or credited for such behavior has not been validated by definitive experimental and theoretical studies. In spite of this uncertainty, during the latter development stages of the test methods, a decision was reached to provide a trough on the specimen holder to collect and permit consumption of some of the molten residue. In processing this standard, questions were raised as to the usefulness of the trough, since the thermal exposure to the material within it is less severe than that to material that remains in the normal specimen position. A small-scale study was conducted. It showed that thermoplastic materials differed widely. Whereas appreciable smoke developed from one material placed in the trough, only a small quantity of smoke developed when another material was placed in the trough. This did not seem, however, to be too different from that performance which might be expected from the same materials in another fire exposure, and thus there does not seem to be any reason to ban from the test thermoplastic materials that melt or drip into the trough.

X4.4 Precision

X4.4.1 In any method, one of the important considerations is the degree to which it, when applied to a given material, will yield constant results. Since this test results in destruction of the specimen, the results of any test to determine precision are affected not only by the random errors that might be inherent in the procedure but also by any variation in the properties of the replicate specimens. Thus, in studying the degree to which experimental results can be repeated within a given laboratory, it is desirable to use a material from which specimens of uniform composition and dimensional characteristics can be prepared.

X4.4.1.1 This fact was recognized in planning the large interlaboratory study of precision of the measurement method. In spite of this, some of the experimental variability observed was undoubtedly related to variations in the replicate specimens. In at least one instance, variation in thickness as great as 20 % was observed. To assist in identifying variability resulting from this cause, requirements for weighing specimens have now been included as a part of the test procedure.

X4.4.2 Various changes were made in the test method description as adopted as compared to the description used to advise for the round-robin test conducted. These included: (1) running additional samples when the results of three specimens are highly variable, (2) maintenance of pilot burner, (3) deletion of data that are inconsistent with the equipment, and (4) improved calibration and alignment procedures. These changes are such that the precision data given should be assumed to be conservative as they relate to the test method adopted. Better precision would be expected if another laboratory round-robin test should be conducted.

X4.4.2.1 When studying the results reported by the various laboratories participating in the round-robin study, it was realized that the test method draft given to the laboratories to follow failed to contain a section describing conditions under which data obtained from the test should be excluded. Section 6 of the test method now contains such information. These data were also excluded when calculating the precision data pre-

sented in Section 14. For instance, certain materials were found to ignite under the nonflaming exposure condition. Obviously, these were not nonflaming results. Another cause for such questioning of data involved results that exceeded the measurement capability of the photometer.

X4.5 Reporting of Results

X4.5.1 One of the obvious needs with a test method of this type is to consider ways in which the experimental data should be reported and used. Early draft versions of this standard contained a recommendation that a correction be applied to the measured D_m by subtracting the smoke deposit on the window following a test. In addition, the current version requires reporting $D_m(\text{corr})$. The reporting of D_m as a preferred measurement result is based on the following facts:

X4.5.1.1 The deposit remaining following a test represents a part of the smoke produced. Thus, it seems irrational to subtract this unless it can be shown that the deposit results from late accumulation following a peak smoke reading. The procedures of the test method seem to make this unlikely.

X4.5.1.2 Experience has shown that the determination of T_c used eventually to calculate $D_m(\text{corr})$, is subject to variations in operator technique during the chamber venting procedure.

X4.5.1.3 The introduction of the correction, while not in itself a significant technical problem, suggests a technical sophistication that simply is not justified on the basis of intended use of the data. The effect of these facts was noticed during analysis of the round-robin experimental data. The results were found to be more consistent for the uncorrected data (D_m).

X4.6 Limitations on Application of Smoke Measurement Data

X4.6.1 The smoke problems that develop during unwanted fires have been recognized for many years. Fire fighters are faced with it daily in their work. However, three problems have tended to prevent application of standards limiting the acceptability of materials or products on the basis of smoke production: (1) the extent to which the smoke measurement assesses the smoke hazard (12, 13); (2) the lack of a well-defined measurement method which could be shown to provide a technically valid means for smoke characterization; and (3) most materials or products, when burning, release large quantities of smoke, and there have been only limited ways of reducing smoke production.

X4.6.1.1 The first problem still exists, although as indicated in X4.2.2.1 there is a valid basis for consideration that this type of smoke measurement does in fact serve to measure the light attenuating properties of the smoke.

X4.6.1.2 The second problem has been partially alleviated with the development of the smoke chamber. However, it must be recognized that only two of a wide range of fire exposure conditions are simulated by the test method. Thus any rank ordering of materials by the test must be recognized as only based on the fire exposure conditions applied and, in fact, the test method develops different rankings depending upon whether a ranking is based upon the nonflaming exposure or the flaming exposure. All of the parameters that affect fire behavior will influence the amount of smoke produced. Thus,

it is unrealistic to place great confidence in the smoke measurement, as unique and absolute measures of smoke production during building fires.

X4.6.1.3 The third problem still remains. If significant changes in smoke levels are to be expected when fire occurs it seems necessary to require large changes in D_m . To limit the type and size of fire that could develop, very severe limitations would have to be placed on smoke production of both the building finish material and the occupancy items, and comprehensive fire prevention and protection measures must be continually maintained.

X4.6.2 It is important to remember that for any given thermal exposure condition, the smoke produced when a fire occurs is related to the thickness and density of material involved. The importance of specimen thickness is well illustrated in Fig. X4.2. The indicated deviations from a linear relationship of D_m with specimen thickness result from the decreasing pyrolysis rate of the specimen as the burning layer progresses into the specimen and, also, from the increasing rate of smoke dropout and condensation as high smoke concentration develops.

X4.6.3 The smoke density chamber provides a means for characterizing smoke production with an accuracy far in excess of any application requirements that could be recommended. It also provides a means for reporting rate of smoke production

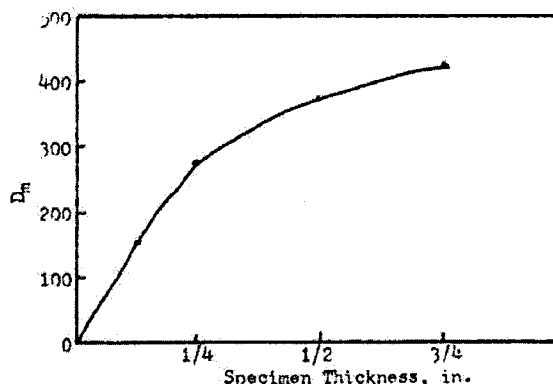


FIG. X4.2 D_m for Spruce as a Function of Specimen Thickness Under Nonflaming Conditions

and time at which specific smoke levels are reached under the test conditions applied. The original paper describing the test method (2) suggested one way these properties could be combined with D_m to yield a smoke obscuration index (SOI). Since then others have suggested refinement of the classification method. It seems that refinements such as these are only likely to be of significant value under the most carefully controlled fire safety conditions.

X5. STANDARD MATERIALS

X5.1 In the 1970s the Office of Standard Reference Materials, National Bureau of Standards (NBS), Gaithersburg, MD, developed two materials, intended for use as standard reference materials for this instrument: a single layer of alpha-cellulose (cotton linters) paper SRM 1006 and a plastic sheet, SRM 1007a. Subsequently, the National Institute of Standards and Technology (NIST), successor to the National Bureau of Standards, developed a new plastic sheet, made of an acrylonitrile-butadiene-styrene copolymer, SRM 1007b. The calibration sheets issued with these materials demonstrated an extreme variability with thickness, so that recommendations were made to assess the thickness to within 0.0005 in. (0.013 mm). Moreover, there is no longer an instrument for Test

Method E 662 at NIST, and the organization does not issue any updates on the materials. Moreover Table 1 and Table 2 indicate that the relative precision of the test method between laboratories can range between 23.0 and 117.7 %, in the flaming mode, and 16.0 and 95.5 %, in the non-flaming mode, so that the test method variability combined with the thickness dependence of the NIST materials, makes their use of low value. More recently, the Federal Aviation Administration also developed a material, intended for use as a standard reference material for this instrument: a phenolic aircraft panel laminated with a fire retarded adhesive, FAA Panel. Use of any standard material does not obviate the need for following the calibration and standardization procedure outlined in this standard.

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- (12) "The Control of Smoke in Building Fires. A State of the Art Review," *Materials Research and Standards*, Vol 11, No. 4, 1971, pp. 16-24.
- (13) Committee E-5 "A Report on Smoke Test Methods," *Standardization News*, August 1976, pp. 18-26.

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APPENDIX B:
Boeing Specification Support Standard BSS 7239

1

SCOPE

This standard covers the test methods for determining the toxic gas generating characteristics of aircraft materials, using the National Bureau of Standards (NBS) Smoke Density Chamber for sample combustion. Gases specifically covered are carbon monoxide (CO), hydrogen cyanide (HCN), nitrogen oxides (NO_x = NO + NO₂), and sulfur dioxide (SO₂). These procedures may be used for other toxic gases if so specified. This test may be conducted simultaneously with the NBS smoke generation test described in Smoke Generation by Materials on Combustion (BSS 7238).

1.1

PURPOSE

The purpose of this specification is to determine the levels of several toxic gases (in ppm) released by a sample during combustion under specified thermal exposure conditions.

1.2

CLASSIFICATION

Not applicable to this specification.

2

APPLICABLE DOCUMENTS

The current issue of the following references shall be a part of this standard to the extent herein indicated:

AMINCO-NBS Smoke Density Chamber, Cat. 4-5800B, Instruction Manual 941-B

NBS Technical Note 708, "Interlaboratory Evaluation of Smoke Density Chamber"

Drägerwerk Ag Lübeck, "Detector Tube Handbook," Second Edition, Available from Suppliers of Dräger Equipment

BSS 7238 Test Method for Smoke Generation by Materials on Combustion

BSS 7242 Determination of the Concentration of Cyanide, Chloride, and Fluoride Ions in Solutions from Combustion

3

CONTENTS

Not applicable to this specification.

4

DEFINITIONS

Not applicable to this specification.

5

TEST SPECIMEN REQUIREMENTS

5.1

Specimen control shall be as specified in BSS 7238 Smoke Generation by Materials on Combustion. A minimum of two specimens shall be tested to measure the evolution of any specific toxicant. If the observed concentration of the toxicant exceeds 50 percent of the maximum permitted value, for either specimen, a third specimen shall be tested.

6

EQUIPMENT/APPARATUS

6.1

COMBUSTION CHAMBER

The NBS Smoke Chamber shall be used for sample combustion.

ACTIVE PAGES: (1) Rev A (2) Rev A (3) Rev A (4) Rev A (5) Rev A (6) Rev A (7) Rev A (8) Rev A (9) Rev A (10) Rev A (11) Rev A

ORIGINAL ISSUE: 10-13-78	REV.: "X" 1-18-86	TEST METHOD FOR TOXIC GAS GENERATION BY MATERIALS ON COMBUSTION	BSS 7239 Page 1 of 11
BY C. H. Thompson / 78	MFG. <i>[Signature]</i>		
CK'D <i>[Signature]</i>	Q.C. <i>[Signature]</i>	BOEING SPECIFICATION SUPPORT STANDARD	
ENG <i>[Signature]</i>	MAT'L <i>[Signature]</i>		

FSCM NO. 81205
8-12788 REV. 8-86

X503

GAS ANALYSIS EQUIPMENT

Certain of the following items will be required, depending upon the specific gases to be measured.

- a. Dräger Multigas Detector, Model 21/32 (Handpump). Available from Safety and Supply Co., 5510 E. Marginal Way South, Seattle, WA 98168.
- b. Colorimetric Gas Detector Tubes, as appropriate for the toxicant to be determined. Available from National Dräger Co., P.O. Box 120, Pittsburgh, PA 15230.
- c. MSA Hand Pump. Available from Mine Safety Appliances (MSA) Co., P.O. Box 426, Pittsburgh, PA 15208.
- d. Hydrogen Chloride Detector Tube, Part No. 91636. Available from Mine Safety Appliances Co.
- e. Digital Timer. A digital timer is recommended for determining the times to initiate and terminate sampling unless automatic timers are used.
- f. Sampling System. A pumping system capable of providing sample flow rates equivalent to those produced by Dräger and MSA hand pumps is recommended in place of hand held pumps when large numbers of tests are to be done. A system producing a flow rate of $6.7 \times 10^{-6} \text{ m}^3/\text{s}$ (400 ml/min.) is required when scrubber sampling is used. Automatic timing controls to begin and end sampling are desirable. Two suitable systems are shown in Figure 1.

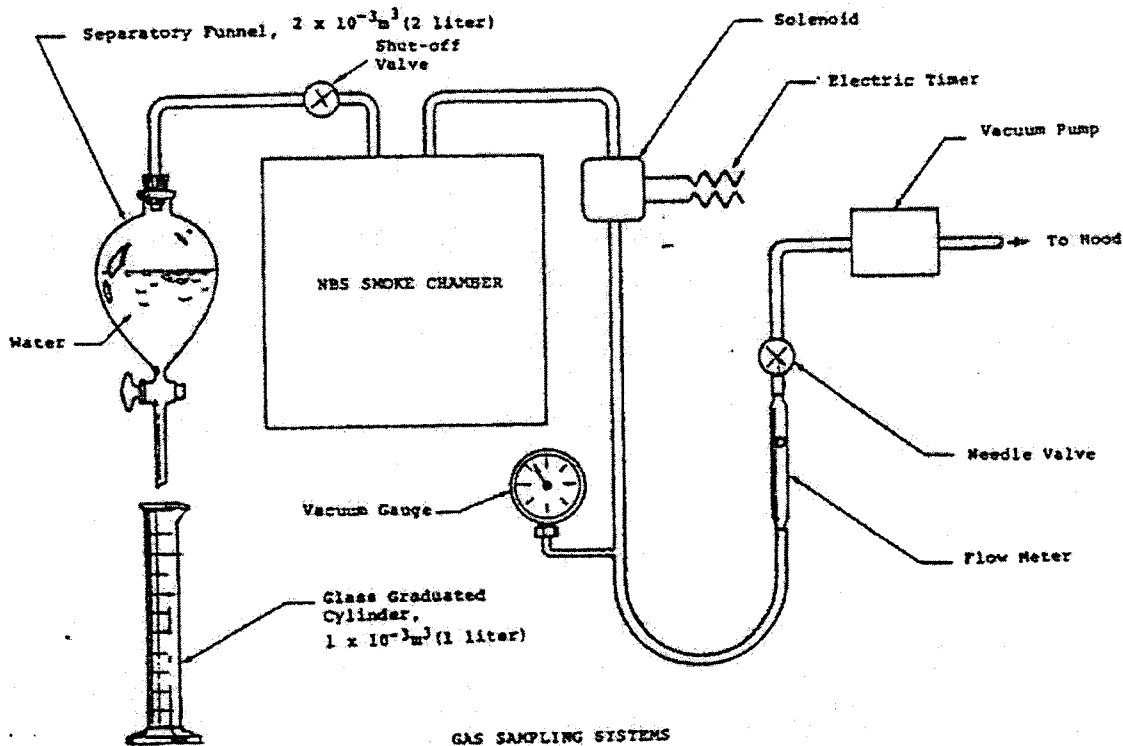


Figure 1.

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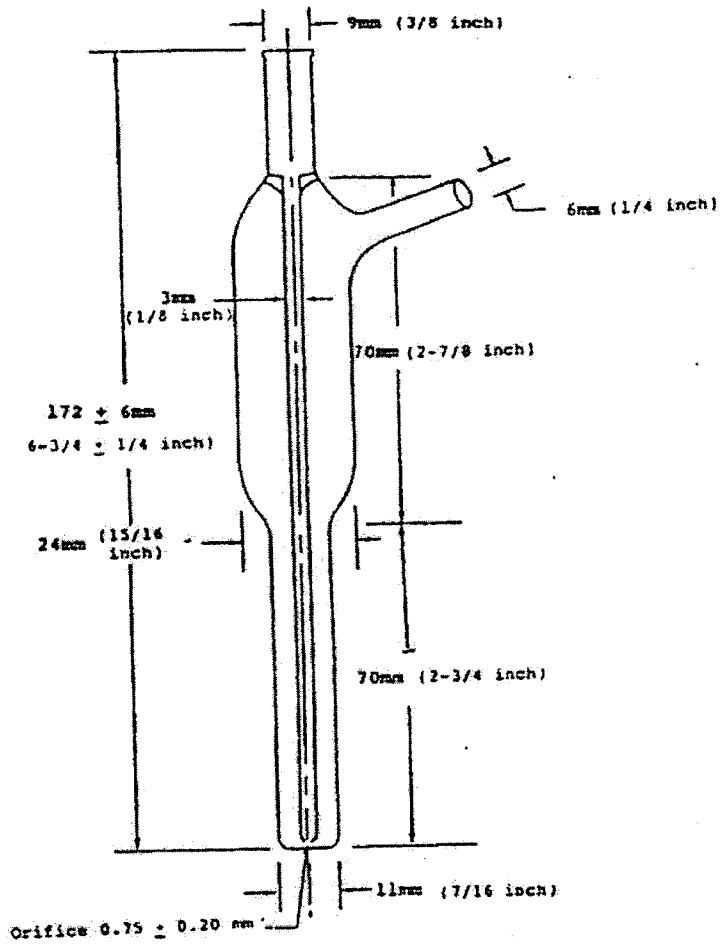
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GAS ANALYSIS EQUIPMENT (Continued)

- g. Gas Scrubbers. Impinger type scrubbers (bubblers) shown in Figure 2 are suitable for absorbing toxic gases into $1.00 \times 10^{-5} \text{m}^3$ (10.0 ml) of absorbing solutions at flow rates of up to $6.7 \times 10^{-6} \text{m}^3/\text{s}$ (400 ml/min). They may be fabricated by any custom glass blower. Other scrubber designs can be used with the approval of The Boeing Company Quality Control, provided data is furnished demonstrating that a scrubbing efficiency of greater than 95 percent is obtainable at the flow rates employed in this test with the toxicant concentrations expected.
- h. High Precision pH-meter. The Orion Model 801 or equivalent is recommended, to provide the accuracy and precision needed when using specific ion electrodes.
- i. Electrodes.
- (1) Fluoride Specific Ion electrode, Orion Model 94-09A or equivalent. Required for determination of HF.
 - (2) Chloride Specific Ion Electrode, Orion Model 94-17A or equivalent. Required for determination of HCl at concentrations above 500 ppm.
 - (3) Cyanide Specific Ion Electrode, Orion Model 94-06 or equivalent. Recommended as an alternate to Dräger tubes for determination of HCN.
 - (4) Double Junction Reference Electrode, Orion Model 94-02 or equivalent. Required for use with above specific ion electrodes.
- j. Continuous Toxic Gas Monitors. Continuous monitoring equipment for any of the gases covered in this specification may be substituted for these analytical methods with the approval of Boeing, provided that information is presented to demonstrate that:
- (1) The equipment is able to measure the toxic gas concentration in the smoke chamber within ± 20 percent.
 - (2) The total quantity of smoke chamber contents withdrawn by all sampling devices during the total duration of the test does not exceed 10 percent of the total volume of the smoke chamber.

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NOTE: All dimensions nominal unless otherwise specified.

IMPINGER TYPE SCRUBBER (BUBBLER)

Figure 2

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7

PROCEDURE

7.1

CALIBRATION

- a. Prior to each day's work the Dräger pump model 21/31 shall be tested as specified in the Dräger Detector Tube Handbook.
- b. Calibration of the colorimetric gas detection tubes is not required. The tubes shall be stored as described in the manufacturer's literature and used before the expiration date printed on the package.
- c. Calibration of any gas sampling system shall be accomplished monthly, and more frequently if any variation in operation is suspected. The calibration procedure shall demonstrate that the system will aspirate the proper volume of gas within ± 5 percent through the detection devices (colorimetric tubes or scrubbers) when operated for the time period and at the flow settings used during test. This may be accomplished either using a soap bubble flowmeter (available from Kin-Tech Laboratories, Inc., Texas City, Texas) or by drawing water into a gas burette attached to the sampling port. A record shall be maintained of these settings, and the causes of any major changes in these values shall be ascertained and corrected.

7.2

TEST PROCEDURES

Approved gas analysis methods for this specification are listed in Table I. Specific gas detection tubes are suitable for the determination of CO, HCN, SO₂, and NO_x (NO + NO₂) in the concentration ranges normally produced in the NBS smoke chamber. A convenient alternative method for CO uses the continuous NDIR monitor listed. Gas detection tubes can be used for low concentrations of HF and HCL; however, the higher concentrations of these gases produced by burning some materials will require gas scrubbing followed by specific ion electrode analysis, as described in BSS 7242, Determination of the Concentration of Cyanide, Chloride, and Fluoride Ions in Solutions from Combustion. Substitution of other analytical techniques is permissible subject to the approval of Boeing Quality Control when data is provided demonstrating that such techniques will produce equivalent results. These tests can be done simultaneously with the smoke generation tests (BSS 7238) without affecting the smoke measurements.

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TABLE I
APPROVED GAS ANALYSIS METHODS

TOXIC GAS	MAXIMUM MEASURABLE CONCENTRATION PPM	ANALYTICAL METHOD	EQUIPMENT REQUIRED	COMMENTS
CO	12,000	Colorimetric Tubes	Pump, Tubes	Higher ranges available
	5,000	Instrumental, Nondispersive Infrared	Beckman Model 854 or equivalent	Furnishes continuous record
HF	15	Colorimetric Tubes	Pump, Tubes	Cannot increase range by decreasing number of pump strokes
	2,500	Scrubbing, Specific Ion Electrode	Precision pH Meter, Fluoride Electrode	See BSS 7242
HCL	100	Colorimetric Tubes	Pump, Tubes	
	500	MSA Tube	MSA Pump, Tubes	
	10,000	Scrubbing, Specific Ion Electrode	Precision pH-Meter, Chloride Electrode	See BSS 7242
NO _x	500	Colorimetric Tubes	Pump, Tubes	Use Nitrous Fumes tubes only
SO ₂	2,000	Colorimetric Tubes	Pumps, Tubes	
HCN	150	Colorimetric Tubes	Pump, Tubes	
	2,500	Scrubbing, Specific Ion Electrode	Precision pH-Meter, Cyanide Electrode	See BSS 7242

7.2.1

SAMPLING TIME

Unless otherwise specified, initiate sampling 240 seconds (4 min.) after beginning the smoke test.

7.2.2

TEST SEQUENCE

(a) Chamber Conditioning

The chamber shall be preconditioned by burning at least four specimens evolving HF immediately before measuring HF evolution from a test material. Either specimens of the test material itself or conditioning specimens with a 3 mil Tedlar coating may be employed. This treatment decreases the rate at which HF is adsorbed by the chamber walls from the chamber atmosphere. Measurement of HF evolution shall immediately follow this conditioning, and reconditioning is necessary whenever an interruption in testing occurs (test of a non-HF evolving material, lunch or overnight break, equipment malfunction, etc.)

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7.2.2

TEST SEQUENCE (Continued)

(b) Colorimetric Gas Detection Tubes

A list of available colorimetric gas detection tubes and of their measuring ranges is given in Table II. Select a tube and number of strokes (or sample volume), so that an on-scale stain will be produced by the toxic gas concentration expected.

TABLE II
AVAILABLE GAS DETECTOR TUBES FOR VARIOUS TOXICANTS

TOXIC GAS	COLORIMETRIC GAS DETECTOR TUBE		NO. OF STROKES N	MEASURING RANGE PPM	COMMENTS		
	TUBE NO.						
CO	10/b		10	10 to 300	Cannot extend range by decreasing number of strokes.		
			5	20 to 600			
			2	50 to 1500			
			1	100 to 3000			
	0.1 percent		1	1000 to 3000			
HF	1.5/b		20	1.5 to 15			
HCl	1/a		10	1 to 10		Requires 40 sec for 1 stroke	
			5	2 to 20			
			2	5 to 50			
			1	10 to 100			
		5	1	0.100			Tubes specific for NO ₂ alone are also available.
		1	1	0 to 500			
NO ₂	0.5/a		5	0.5 to 10			
SO ₂	2/a		10	2 to 50	NO ₂ produces negative interference. B ₂ S produces positive interference.		
			5	5 to 100			
	20/a		2	20 to 500			
			10	1 to 20			
	1/a		5	2 to 40			
			2	5 to 100			
20/a		10	20 to 200				
		5	40 to 400				
		2	100 to 1000				
		1	200 to 2000				
HCN	2/a		5	2 to 30			
			2	5 to 75			
			1	10 to 150			

- Break off the ends of the detector tube. Attach it as shown in Figure 3 to a gas sampling port of the MBS chamber. A total of four detector tubes and/or bubblers may be installed for a single smoke run.
- Attach a handpump (Dräger or MSA) or the gas sampling system to the external opening of the MBS chamber gas sampling port.
- At the designated time during the smoke test, open the valve in the chamber sampling port and either activate the hand pump for the proper number of strokes or draw the proper volume of gas through the tube using the gas sampling system, at the proper flow rate for the specific tube.

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7.2.2

TEST SEQUENCE (Continued)

(4) After completing the smoke test and purging the chamber, note the stain (color change) produced. Discard any result if flow blockage due to soot deposition has occurred.

(5) Record the following:

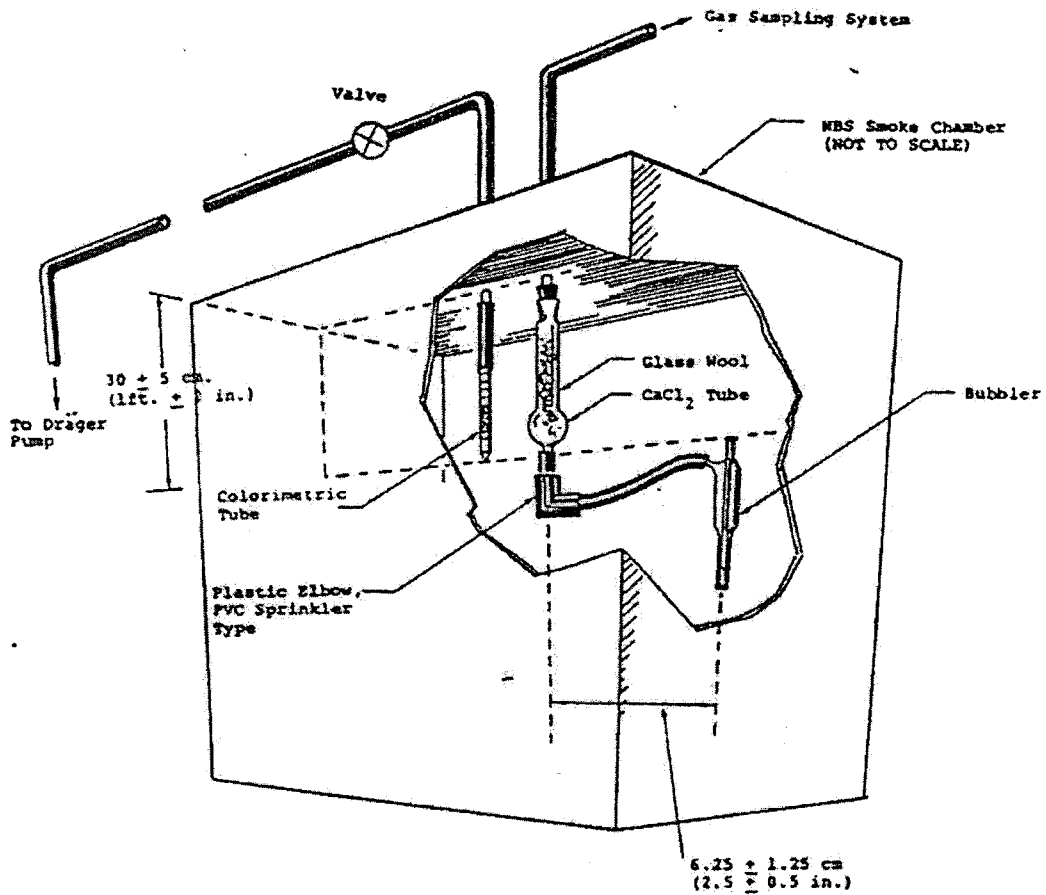
- Sample Identification
- Smoke Test Run Number
- Test Conditions (flux, flaming or smoldering, etc.)
- Time of Initiating Sample
- Duration of Sampling
- Tube Used (Toxicant, Part No.)
- Lx (ppm) - length of observed stain where x is specific toxicant
- n_0 = standard number of strokes for tube
- n = actual number of strokes used
- or
- v_0 = standard value for tube used
 $= n_0 \cdot 1.00 \times 10^{-4} \text{ m}^3$ (100 ml)
- v = volume aspirated - $n \cdot 1.00 \times 10^{-4} \text{ m}^3$
- f = flowmeter reading during sampling, if flow system used
- cx (ppm) = measured concentration of toxicant x in smoke chamber
 $= \frac{Lx}{\text{ppm}} \cdot \frac{n_0}{n}$ or $\frac{Lx}{\text{ppm}} \cdot \frac{v_0}{v}$

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7.2.2

TEST SEQUENCE (Continued)



INSTALLATION OF SAMPLING DEVICES IN SMOKE CHAMBER

Figure 3

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7.2.3

GAS SCRUBBERS

- a. Place $1.00 \times 10^{-5} \text{ m}^3$ (10.0 ml) of 0.1 M sodium hydroxide solution in a clean, dry bubbler. Avoid wetting the gas inlet tube above the liquid level.
- b. Prior to the test, attach the bubbler to a gas sampling port of the NBS chamber as shown in Figure 3.
- c. At the designated time during the test, open the valve in the sampling line. Adjust the flow rate to $6.7 \times 10^{-6} \text{ m}^3/\text{s}$ (400 ml/min) and continue until 10^{-3} m^3 (1 liter), unless otherwise specified, has been aspirated.
- d. After completing the smoke test and purging the chamber, rinse the gas inlet tube by using a rubber bulb to draw absorbing solution up into the tube several times being cautious not to let the solution reach the bulb. Transfer the bubbler contents to a screw capped plastic bottle for subsequent analysis.
- e. Record the following:

Sample Identification

Test Conditions (flux, flaming or smoldering)

Run Number

Sampling Port Location

Time of Initiating Sampling

Duration of Sampling

Flowmeter Setting During Sampling

- f. As soon as possible, preferably on the day of testing, and in no case later than 72 hours following completion of a test series, analyze the solutions using the analytical methods described in BSS 7242. Record the following data:

C_M^x = Measured molar concentration of analyte in the bubbler solution.

C^x (ppm) = $C_M^x \cdot F$ = Concentration of toxicant in parts per million in NBS chamber atmosphere,

where

x = Specific toxicant measured

F = Analytical Factor = 2.5×10^5 for a 10^{-3} m^3 (1 liter) gas sample at 30 degrees C and 10^5 Pa (1 atm) pressure, scrubbed by $1.00 \times 10^{-5} \text{ m}^3$ (10.0 ml) of absorbing solution

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7.3

CALCULATIONS

For each toxicant measured, calculate the average value of C (ppm) and the standard deviation as follows:

$$\overline{C}_{\text{ppm}}^x = \frac{\sum C_{\text{ppm}}^x}{n}$$

$$s^x = \sqrt{\frac{n \sum (C_{\text{ppm}}^x)^2 - (\sum C_{\text{ppm}}^x)^2}{n(n-1)}}$$

where:

$\overline{C}_{\text{ppm}}^x$ = Average value of C_{ppm}^x

$\sum C_{\text{ppm}}^x$ = Sum of measured C_{ppm}^x values

$\sum (C_{\text{ppm}}^x)^2$ = Sum of squared C_{ppm}^x values

n = Number of individual values of C_{ppm}^x
(Note this is not equivalent to the use of symbol n in Section 7.2.2b.(5))

s^x = Measurement standard deviation for toxicants

B

REPORTING

The test report for this specification may be combined with the smoke density test report of BSS 7238. The following data on each specimen shall be reported unless otherwise specified.

- a. Complete specimen identification, i.e. material composition and construction, alpha-numeric identifier, thickness, and weight.
- b. Test conditions, e.g. radiant flux, flaming or smoldering, etc.
- c. The analytical method used in measuring C_{ppm}^x .
- d. The values of C^x (ppm) at 240 seconds (4 min), unless otherwise specified, for each toxicant tested.
- e. The values of $\overline{C^x}$ (ppm) and of s^x for each toxicant measured.
- f. Comparison of the $\overline{C_{\text{ppm}}^x}$ values with the requirements as called out in the applicable specification.

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**APPENDIX C:
ASTM E1354**



Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter¹

This standard is issued under the fixed designation E 1354; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This fire-test-response standard provides for measuring the response of materials exposed to controlled levels of radiant heating with or without an external ignitor.

1.2 This test method is used to determine the ignitability, heat release rates, mass loss rates, effective heat of combustion, and visible smoke development of materials and products.

1.3 The rate of heat release is determined by measurement of the oxygen consumption as determined by the oxygen concentration and the flow rate in the exhaust product stream. The effective heat of combustion is determined from a concomitant measurement of specimen mass loss rate, in combination with the heat release rate. Smoke development is measured by obscuration of light by the combustion product stream.

1.4 Specimens shall be exposed to heating fluxes in the range of 0 to 100 kW/m². External ignition, when used, shall be by electric spark. The value of the heating flux and the use of external ignition are to be as specified in the relevant material or performance standard (see X1.2). The normal specimen testing orientation is horizontal, independent of whether the end-use application involves a horizontal or a vertical orientation. The apparatus also contains provisions for vertical orientation testing; this is used for exploratory or diagnostic studies only.

1.5 Ignitability is determined as a measurement of time from initial exposure to time of sustained flaming.

1.6 This test method has been developed for use for material and product evaluations, mathematical modeling, design purposes, or development and research. Examples of material specimens include portions of an end-use product or the various components used in the end-use product.

1.7 The values stated in SI units are to be regarded as the standard.

1.8 *This standard is used to measure and describe the response of materials, products, or assemblies to heat and*

flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. For specific hazard statements, see Section 7.*

2. Referenced Documents

2.1 ASTM Standards:²

D 5865 Test Method for Gross Calorific Value of Coal and Coke

E 176 Terminology of Fire Standards

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E 662 Test Method for Specific Optical Density of Smoke Generated by Solid Materials

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E 906 Test Method for Heat and Visible Smoke Release Rates for Materials and Products

2.2 ISO Standards:

ISO 5657-1986(E) Fire Tests—reaction to fire—ignitability of building materials³

ISO 5725 Precision of test methods—determination of repeatability and reproducibility for a standard test method by inter-laboratory tests³

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology E 176.

3.2 *Definitions of Terms Specific to This Standard:*

¹ This test method is under the jurisdiction of ASTM Committee E05 on Fire Standards and is the direct responsibility of Subcommittee E05.21 on Smoke and Combustion Products.

Current edition approved April 1, 2004. Published May 2004. Originally approved in 1990. Last previous edition approved in 2004 as E 1354 - 04.

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

3.2.1 *effective heat of combustion, n*—the measured heat release divided by the mass loss for a specified time period.

3.2.2 *heating flux, n*—the incident flux imposed externally from the heater on the specimen at the initiation of the test.

3.2.2.1 *Discussion*—The specimen, once ignited, is also heated by its own flame.

3.2.3 *heat release rate, n*—the heat evolved from the specimen, per unit of time.

3.2.4 *ignitability, n*—the propensity to ignition, as measured by the time to sustained flaming, in seconds, at a specified heating flux.

3.2.5 *net heat of combustion, n*—the oxygen bomb (see Test Method D 5865) value for the heat of combustion, corrected for gaseous state of product water.

3.2.6 *orientation, n*—the plane in which the exposed face of the specimen is located during testing, either vertical or horizontal facing up.

3.2.7 *oxygen consumption principle, n*—the expression of the relationship between the mass of oxygen consumed during combustion and the heat released.

3.2.8 *smoke obscuration, n*—reduction of light transmission by smoke, as measured by light attenuation.

3.2.9 *sustained flaming, n*—existence of flame on or over most of the specimen surface for periods of at least 4 s.

3.2.9.1 *Discussion*—Flaming of less than 4 s duration is identified as flashing or transitory flaming.

3.3 Symbols:

A_s	= nominal specimen exposed surface area, 0.01 m ² .
C	= calibration constant for oxygen consumption analysis, m ^{1/2} - kg ^{1/2} - K ^{1/2} .
Δh_c	= net heat of combustion, kJ/kg.
$\Delta h_{c,eff}$	= effective heat of combustion, kJ/kg.
I	= actual beam intensity.
I_o	= beam intensity with no smoke.
k	= smoke extinction coefficient, m ⁻¹ .
L	= extinction beam path length, m.
m	= specimen mass, kg.
m_f	= final specimen mass, kg.
m_i	= initial specimen mass, kg.
\dot{m}	= specimen mass loss rate, kg/s.
ΔP	= orifice meter pressure differential, Pa.
q''_{tot}	= total heat released, kJ/m ² (Note that kJ = kW·s).
\dot{q}	= heat release rate, kW.
q''	= heat release rate per unit area, kW/m ² .
q''_{max}	= maximum heat release rate per unit area (kW/m ²).
q''_{180}	= average heat release rate, per unit area, over the time period starting at t_{ig} and ending 180 s later (kW/m ²).
r	= repeatability (the units are the same as for the variable being characterized).
R	= reproducibility (the units are the same as for the variable being characterized).
r_o	= stoichiometric oxygen/fuel mass ratio (-).
s_r	= sample-based standard deviation estimate for repeatability (same units as r).
s_R	= sample-based standard deviation estimate for reproducibility (same units as R).

t	= time, s.
t_d	= oxygen analyzer delay time, s.
t_{ig}	= time to sustained flaming (s).
ρ	= density (kg/m ³).
Δt	= sampling time interval, s.
T_c	= absolute temperature of gas at the orifice meter, K.
\dot{V}	= volume exhaust flow rate, measured at the location of the laser photometer, m ³ /s.
X_{O_2}	= oxygen analyzer reading, mole fraction O ₂ (-).
$X_{O_2,i}$	= initial value of oxygen analyzer reading (-).
X_{O_2}	= oxygen analyzer reading, before delay time correction (-).
σ_f	= specific extinction area, for smoke, m ² /kg.
σ_r	= repeatability standard deviation (same units as r).
σ_R	= reproducibility standard deviation (same units as R).

4. Summary of Test Method

4.1 This test method is based on the observation (1)⁴ that, generally, the net heat of combustion is directly related to the amount of oxygen required for combustion. The relationship is that approximately 13.1 × 10³ kJ of heat are released per 1 kg of oxygen consumed. Specimens in the test are burned in ambient air conditions, while being subjected to a predetermined external heat flux, which can be set from 0 to 100 kW/m². Burning may be either with or without a spark ignition. The primary measurements are oxygen concentrations and exhaust gas flow rate. Additional measurements include the mass-loss rate of the specimen, the time to sustained flaming and smoke obscuration, or as required in the relevant material or performance standard.

5. Significance and Use

5.1 This test method is used primarily to determine the heat evolved in, or contributed to, a fire involving products of the test material. Also included is a determination of the effective heat of combustion, mass loss rate, the time to sustained flaming, and smoke production. These properties are determined on small size specimens that are representative of those in the intended end use.

5.2 This test method is applicable to various categories of products and is not limited to representing a single fire scenario. Additional guidance for testing is given in XI.2.3 and XI.11.

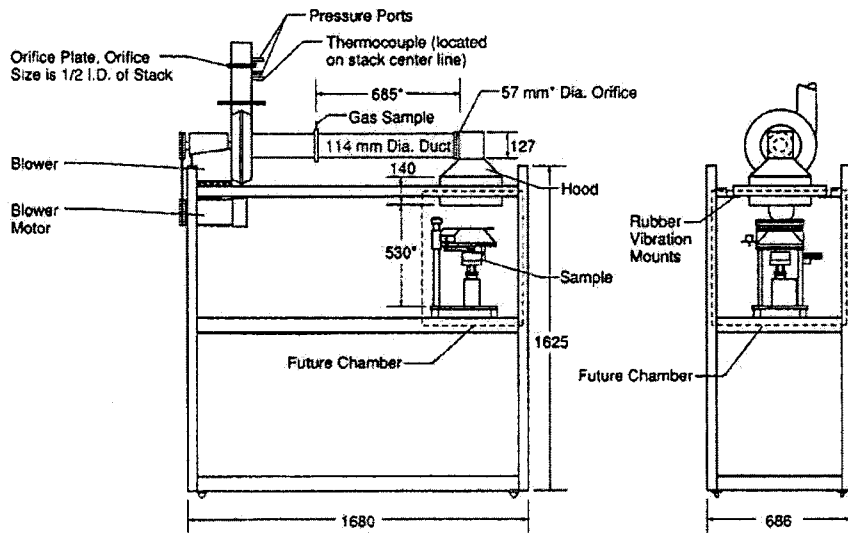
5.3 This test method is not applicable to end-use products that do not have planar, or nearly planar, external surfaces.

6. Apparatus

6.1 General:

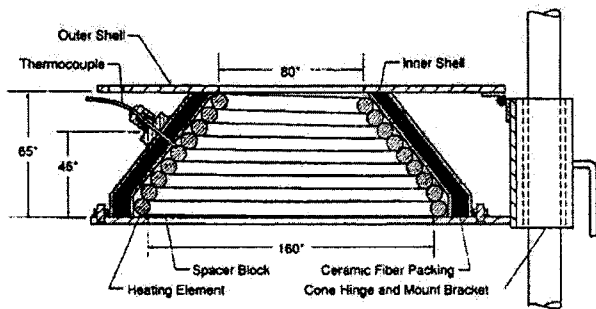
6.1.1 All dimensions given in the figures that are followed by an asterisk are mandatory, and shall be followed within nominal tolerances of ±1 mm, unless otherwise specified. Particularly critical dimensions are followed by an asterisk in Figs. 1-12.

⁴ The boldface numbers in parentheses refer to the list of references at the end of this test method.



NOTE 1—All dimensions are in millimetres.
NOTE 2—* Indicates a critical dimension.

FIG. 1 Overall View of Apparatus



NOTE 1—All dimensions are in millimetres.
NOTE 2—* Indicates a critical dimension.

FIG. 2 Cross-Section View Through the Heater

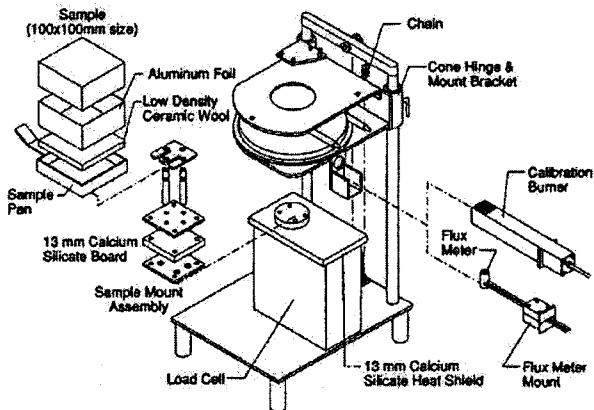


FIG. 3 Exploded View, Horizontal Orientation

6.1.2 The test apparatus⁵ shall consist essentially of the following components: a conical radiant electric heater, capable of horizontal or vertical orientation; specimen holders, different for the two orientations; an exhaust gas system with oxygen monitoring and flow measuring instrumentation; an electric ignition spark plug; a data collection and analysis system; and a load cell for measuring specimen mass loss. A general view of the apparatus is shown in Fig. 1; a cross section through the heater in Fig. 2; and exploded views of horizontal and vertical orientations in Fig. 3 and Fig. 4.

6.1.3 Additional details describing features and operation of the test apparatus are given in Ref (2).

6.2 Conical Heater:

6.2.1 The active element of the heater shall consist of an electrical heater rod, rated at 5000 W at 240 V, tightly wound

into the shape of a truncated cone (Fig. 2 and Fig. 4). The heater shall be encased on the outside with a double-wall stainless steel cone, packed with a refractory fiber material of approximately 100 kg/m³ density.

6.2.2 The heater shall be hinged so it can be swung into either a horizontal or a vertical orientation. The heater shall be capable of producing irradiances on the surface of the specimen of up to 100 kW/m². The irradiance shall be uniform within the central 50 by 50-mm area of the specimen to within ±2 % in the horizontal orientation and to within ±10 % in the vertical orientation. As the geometry of the heater is critical, the dimensions on Fig. 2 are mandatory.

6.2.3 The irradiance from the heater shall be capable of being held at a preset level by means of a temperature controller and three type K stainless steel sheathed thermocouples, symmetrically disposed and in contact with, but not welded to, the heater element (see Fig. 2). The thermocouples

⁵ A list of suppliers of this apparatus is available from ASTM Headquarters.

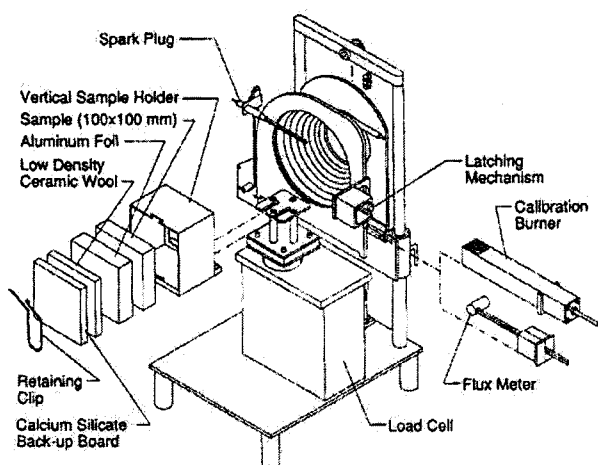


FIG. 4 Exploded View, Vertical Orientation

shall be of equal length and wired in parallel to the temperature controller. The standard thermocouples are sheathed, 1.5 and 1.6 mm outside diameter, with an unexposed hot junction. Alternatively, either 3 mm outside diameter sheathed thermocouples with an exposed hot junction or 1 mm outside diameter sheathed thermocouples with unexposed hot junction can be used.

6.3 Temperature Controller:

6.3.1 The temperature controller for the heater shall be capable of holding the element temperature steady to within $\pm 2^\circ\text{C}$. A suitable system is a 3-term controller (proportional, integral, and derivative) and a thyristor unit capable of switching currents up to 25 A at 240 V.

6.3.2 The controller shall have a temperature input range of 0 to 1000°C ; a set scale capable of being read to 2°C or better; and automatic cold junction compensation. The controller shall be equipped with a safety feature such that in the event of an open circuit in the thermocouple line, it will cause the temperature to fall to near the bottom of its range.

6.3.3 The thyristor unit shall be of the zero crossing and not of the phase angle type.

6.3.4 The heater temperature shall be monitored by a meter capable of being read to $\pm 2^\circ\text{C}$, or better. It shall be permitted to be incorporated into the temperature controller.

6.4 Exhaust System:

6.4.1 The exhaust-gas system shall consist of a high temperature centrifugal exhaust fan, a hood, intake and exhaust ducts for the fan, and an orifice plate flowmeter (Fig. 5). The exhaust system shall be capable of developing flows from 0.012 to $0.035\text{ m}^3/\text{s}$.

6.4.2 A restrictive orifice (57 mm inside diameter) shall be located between the hood and the duct to promote mixing.

6.4.3 A ring sampler shall be located in the fan intake duct for gas sampling, 685 mm from the hood (Fig. 1). The ring sampler shall contain twelve holes to average the stream composition with the holes facing away from the flow to avoid soot clogging.

6.4.4 The temperature of the gas stream shall be measured using a 1.0 to 1.6 mm outside diameter sheathed-junction

thermocouple or a 3 mm outside diameter exposed junction thermocouple positioned in the exhaust stack on the centerline and 100 mm upstream from the measuring orifice plate.

6.4.5 The flow rate shall be determined by measuring the differential pressure across a sharp-edged orifice (57 mm inside diameter) in the exhaust stack, at least 350 mm downstream from the fan when the latter is located as shown in Fig. 5.

6.4.6 In other details, the geometry of the exhaust system is not critical. Where necessary, small deviations from the recommended dimensions given in Fig. 5 shall be permitted to be made. The inner diameter of the duct and the orifice plates is not a critical dimension. Also the fan does not need to be at the exact location as indicated on Fig. 5, but shall be permitted to be further downstream, allowing for a more common type of fan to be used. In this case, sufficient undisturbed inflow distances to the gas sampling probe and the measuring orifice shall be provided for the flow to be uniformly mixed.

6.5 *Load Cell*—The general arrangement of the specimen holders on the load cell is indicated in Fig. 3 and Fig. 4. The load cell shall have an accuracy of 0.1 g, and shall have a total weighing range of at least 3.5 kg of which at least 500 g shall be available for direct monitoring during any single test.

6.6 Specimen Mounting:

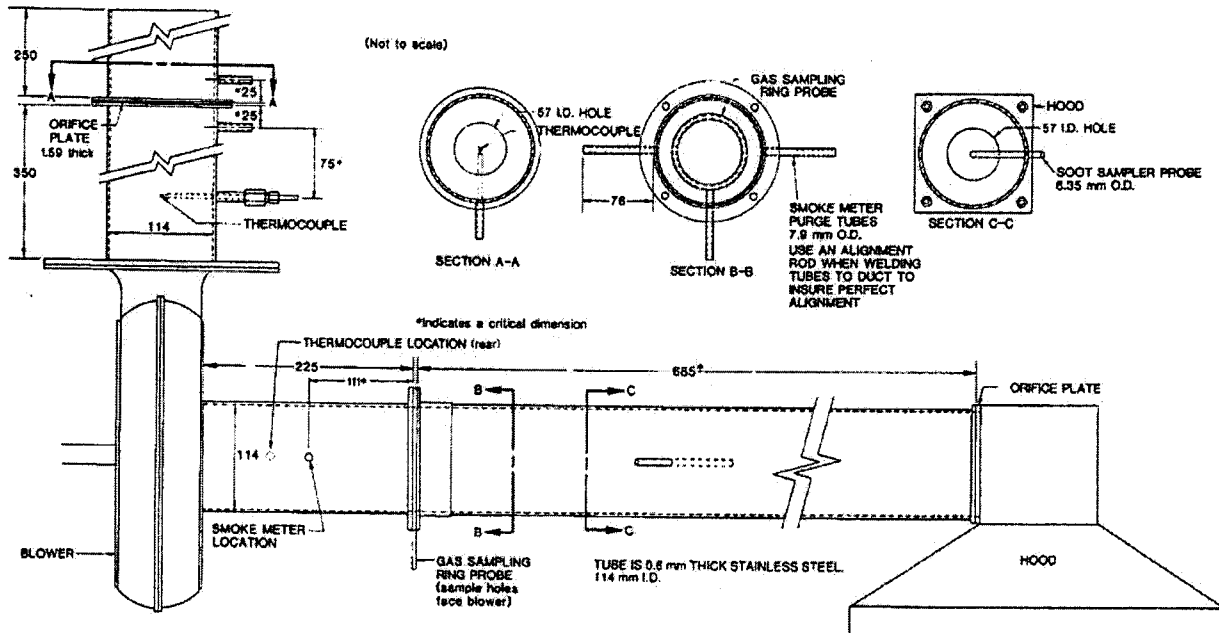
6.6.1 The horizontal specimen holder is shown in Fig. 6.

6.6.2 The bottom of the horizontal specimen holder shall be lined with a layer of low density (nominal density 65 kg/m^3) refractory fiber blanket with a thickness of at least 13 mm. The distance between the bottom surface of the cone heater and the top of the specimen shall be adjusted to be 25 mm. For mechanisms constructed according to the drawing in Fig. 2, this is accomplished by using the sliding cone height adjustment.

6.6.3 The vertical specimen holder is shown in Fig. 7 and includes a small drip tray to contain a limited amount of molten material. A specimen shall be installed in the vertical specimen holder by backing it with a layer of refractory fiber blanket (nominal density 65 kg/m^3), the thickness of which depends on specimen thickness, but shall be at least 13 mm thick. A layer of rigid, ceramic fiber millboard shall be placed behind the fiber blanket layer. The millboard thickness shall be such that the entire assembly is rigidly bound together once the retaining spring clip is inserted behind the millboard. In the vertical orientation, the cone heater height is set so the center lines up with the specimen center.

6.6.4 The testing technique to be used when testing intumescent specimens in the horizontal orientation shall be documented in the test report. Options include the retainer frame (Fig. 12) and wire grid (Fig. 8). The edge frame is used to reduce unrepresentative edge burning of specimens while the wire grid is used for retaining specimens prone to delamination. The wire grid shown in Fig. 8 is also suitable for the vertical orientation.

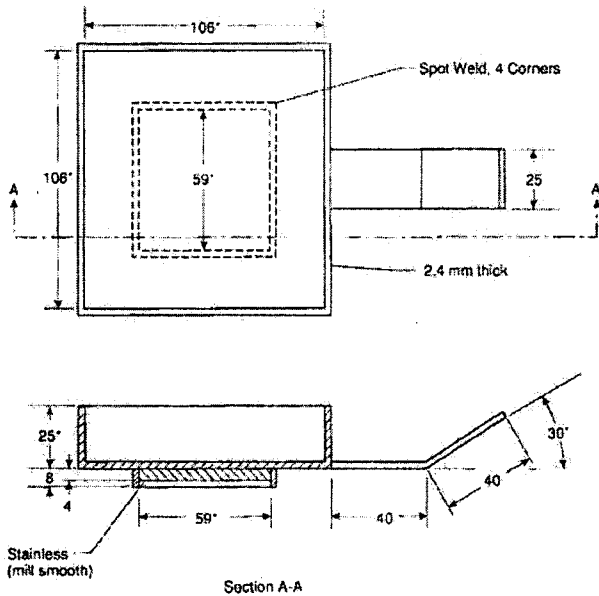
6.7 *Radiation Shield*—The cone heater shall be provided with a removable radiation shield to protect the specimen from the heat flux prior to the start of a test. The shield shall be made of noncombustible material with a total thickness not to exceed 12 mm. The shield shall be one of the following:



NOTE—All dimensions are in millimetres (not to scale).

NOTE 1—All dimensions are in millimetres (not to scale).

FIG. 5 Exhaust System



NOTE 1—All dimensions are in millimetres.

NOTE 2—* Indicates a critical dimension.

FIG. 6 Horizontal Specimen Holder

(a) water cooled and coated with a durable matte black finish of surface emissivity $\epsilon = 0.95 \pm 0.05$ or

(b) not water cooled with a metallic reflective top surface to minimize radiation transfer.

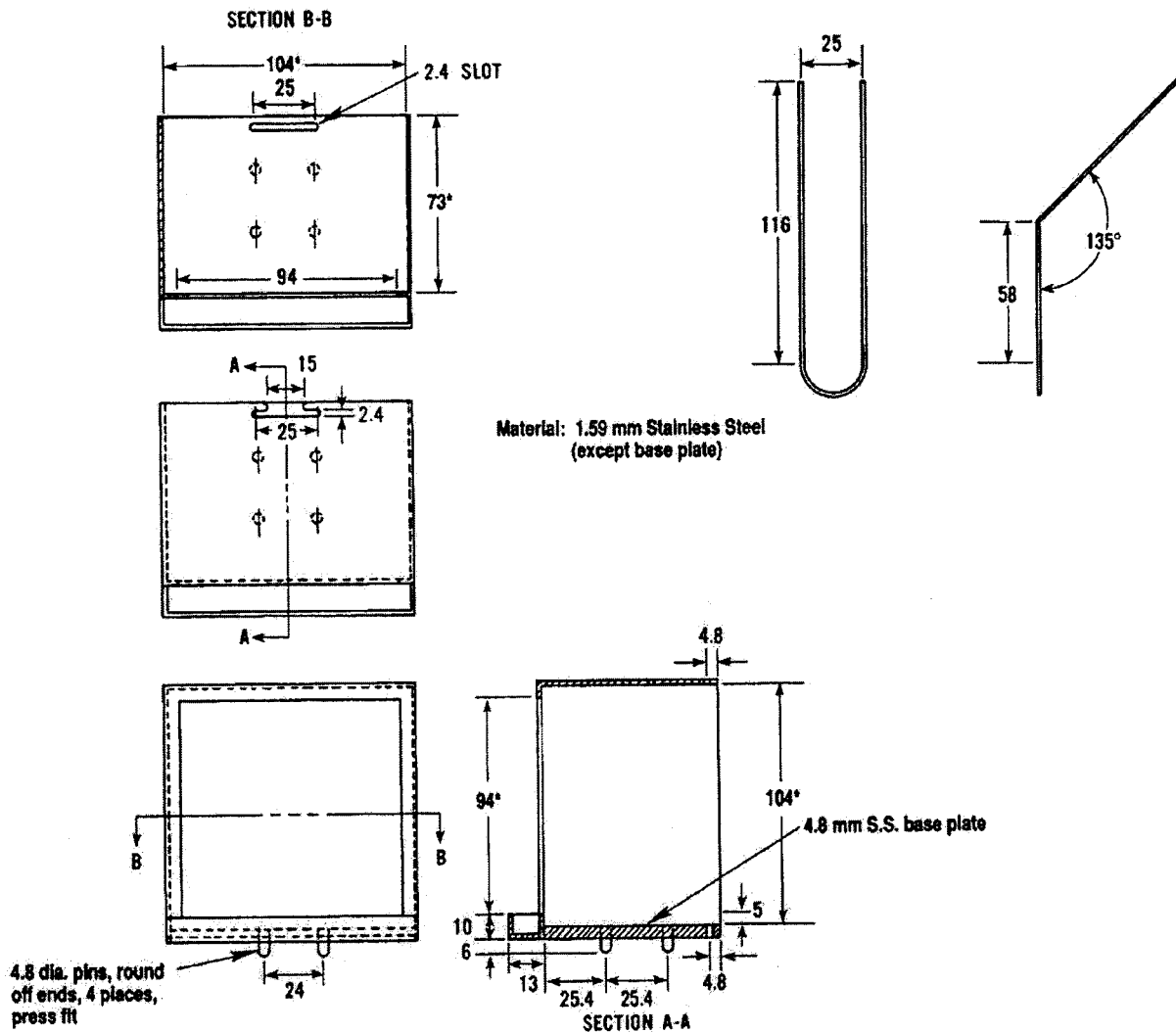
(c) not water-cooled, with a ceramic, non-metallic, surface that minimizes radiation transfer to the specimen surface.

The shield shall be equipped with a handle or other suitable means for quick insertion and removal. The cone heater base plate shall be equipped with the means for holding the shield in position and allowing its easy and quick removal.

6.8 *Ignition Circuit*—External ignition is accomplished by a 10-kV discharge across a 3-mm spark gap located 13 mm above the center of the specimen in the horizontal location; in the vertical orientation the gap is located in the specimen face plane and 5 mm above the top of the holder. A suitable power source is a transformer designed for spark-ignition use or a spark generator. The high voltage connections to the spark electrodes shall not be grounded to the chassis in order to minimize interference with the data-transmission lines. For testing with electric spark ignition, spark discharge shall be continuously operating at 50 to 60 Hz until sustained flaming is achieved. The ignitor shall be removed when sustained flaming is achieved.

6.9 *Ignition Timer*—The timing device for measuring time to sustained flaming shall be capable of recording elapsed time to the nearest second and shall be accurate to within 1 s in 1 h.

6.10 *Gas Sampling*—Gas sampling arrangements are shown in Fig. 9. They shall incorporate a pump, a filter to prevent entry of soot, a cold trap to remove most of the moisture, a bypass system set to divert all flow except that required for the



NOTE 1—All dimensions are in millimetres except where noted.
 NOTE 2—* Indicates a critical dimension.

FIG. 7 Vertical Specimen Holder

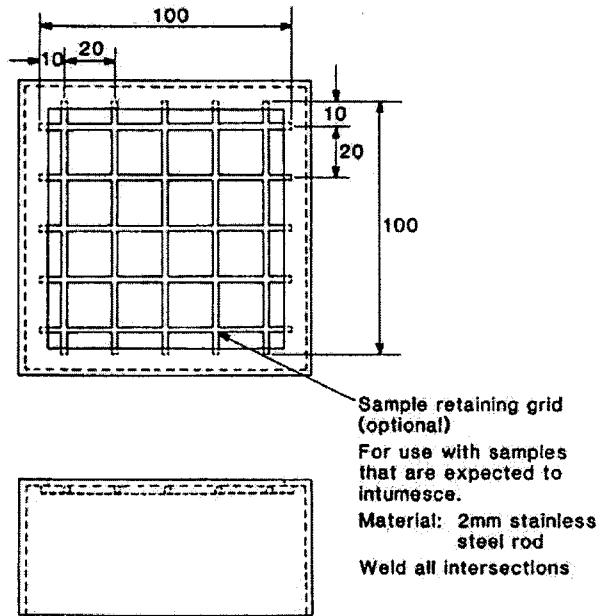
oxygen analyzer, a further moisture trap, and a trap for carbon dioxide (CO₂) removal; the latter if CO₂ is not measured. When a CO₂ trap is used, the sample stream entering the oxygen analyzer must be fully dry; some designs of CO₂ traps require an additional moisture trap downstream of the CO₂ trap.

NOTE 1—If an optional CO₂ analyzer is used instead of removing CO₂ from the oxygen analyzer stream, the equations to calculate the rate of heat release will be different from those for the standard case (Section 12) and are, instead, given in Annex A1.

6.11 *Oxygen Analyzer*—The analyzer shall be of the paramagnetic type with a range from 0 to 25 % oxygen. The analyzer shall exhibit a linear response and drift of not more than ±50 ppm oxygen (root-mean-square value) over a period

of ½ h. Since oxygen analyzers are sensitive to stream pressures, the stream pressure shall be regulated (upstream of the analyzer) to allow for flow fluctuations, and the readings from the analyzer compensated with an absolute pressure regulator to allow for atmospheric pressure variations. The analyzer and the absolute pressure regulator shall be located in a constant-temperature environment. The oxygen analyzer shall have a 10 to 90 % response time of less than 12 s.

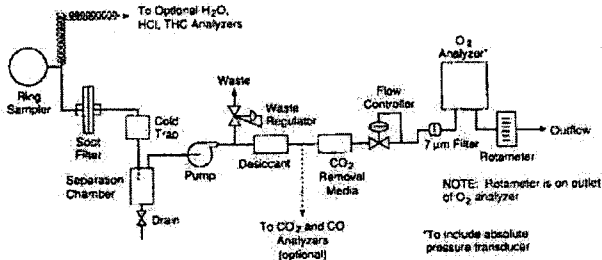
6.12 *Smoke Obscuration Measuring System*—The smoke measuring system (Fig. 10) comprises a helium-neon laser, silicon photodiodes as main beam and reference detectors, and appropriate electronics to derive the extinction coefficient and to set the zero reading. The system is designed to be resiliently attached to the exhaust duct by means of refractory gasketing,



Material: Stainless steel, 1.9 mm thick

NOTE 1—All dimensions are in millimetres.

FIG. 8 Optional Wire Grid (For Horizontal or Vertical Orientation)



NOTE 1—Rotameter is on outlet of the oxygen (O₂) analyzer.

FIG. 9 Gas Analyzer Instrumentation

at the location shown in Fig. 5. This shall be achieved by one of the following options: (a) the use of an optical bench, or (b) the use of a split yoke mounting comprising two pieces that are rigidly screwed together. The meter is located in place by means of two small-diameter tubes welded onto each side of the exhaust duct. These serve as part of the light baffling for the air purging and also serve to aid in the desposition on the tube walls of any smoke that enters despite the purge flow, so that it does not reach the optical elements.

6.13 Heat Flux Meter:

6.13.1 The total heat fluxmeter shall be of the Gardon (foil) or Schmidt-Boelter (thermopile) type with a design range of about 100 kW/m². The sensing surface of the fluxmeter shall be flat, circular, approximately 12.5 mm in diameter, and coated with a durable matte-black finish. The fluxmeter shall be water cooled. Radiation shall not pass through any window before reaching the sensing surface. The instrument shall be robust,

simple to set up and use, and stable in calibration. The instrument shall have an accuracy of within ±3%.

6.13.2 The calibration of the heat fluxmeter shall be checked whenever a recalibration of the apparatus is carried out by comparison with an instrument (of the same type as the working heat fluxmeter and of similar range) held as a reference standard and not used for any other purpose. The reference standard shall be fully calibrated at a standardizing laboratory at yearly intervals.

6.13.3 This meter shall be used to calibrate the heater temperature controller (Fig. 3 and Fig. 4). It shall be positioned at a location equivalent to the center of the specimen face in either orientation during this calibration.

6.14 Calibration Burner—To calibrate the rate of heat release apparatus, a burner is used (Fig. 3 and Fig. 4). The burner is constructed from a square-section brass tube with a square orifice covered with wire gauze through which the methane diffuses (Fig. 11). The tube is packed with ceramic fiber to improve uniformity of flow. The calibration burner is suitably connected to a metered supply of methane of at least 99.5% purity.

6.15 Optical Calibration Filters—Glass neutral density filters, of at least two different values accurately calibrated at the laser wavelength of 0.6328 µm, are required.

6.16 Digital Data Collection—The data collection system used must have facilities for the recording of the output from the oxygen analyzer, the orifice meter, the thermocouples, the load cell, and the smoke measuring system. The data collection system shall have an accuracy corresponding to at least 50 ppm oxygen for the oxygen channel, 0.5°C for the temperature measuring channels, and 0.01% of full-scale instrument output for all other instrument channels. The system shall be capable of recording data for at least 1 h, at intervals not exceeding 5 s.

7. Hazards

7.1 The test procedures involve high temperatures and combustion processes. Therefore, hazards exist for burns, ignition of extraneous objects or clothing, and for inhalation of combustion products. The operator shall use protective gloves for insertion and removal of test specimens. Neither the cone heater nor the associated fixtures shall be touched while hot except with the use of protective gloves. The possibility of the violent ejection of molten hot material or sharp fragments from some kinds of specimens when irradiated cannot totally be discounted and eye protection shall be worn.

7.2 The exhaust system shall be checked for proper operation before testing and must discharge into a building exhaust system with adequate capacity. Provision shall be made for collecting and venting any combustion products that are not collected by the normal exhaust system of the apparatus.

8. Test Specimens

8.1 Size and Preparation:

8.1.1 Test specimens shall be 100 by 100 mm in area, up to 50-mm thick, and cut to be representative of the construction of the end-use product. For products of normal thickness greater than 50 mm, the requisite specimens shall be obtained by cutting away the unexposed face to reduce the thickness to 50

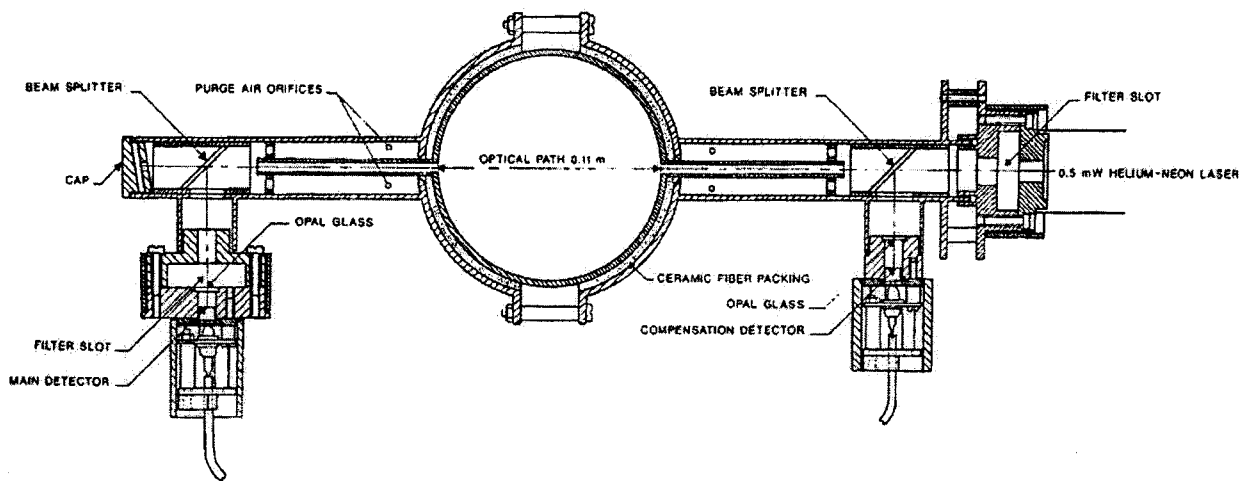


FIG. 10 Smoke Obscuration Measuring System

mm. For testing, wrap specimens in a single layer of aluminum foil, shiny side toward the specimen, covering the sides and bottom. Foil thickness shall be 0.025 to 0.04 mm.

8.1.2 Expose composite specimens in a manner typical of the end-use condition. Prepare them so the sides are covered with the outer layer(s) or otherwise protected.

8.1.3 Some composite and intumescent materials require special mounting and retaining techniques to retain them adequately within the specimen holder during combustion. Such mounting techniques include the use of an edge frame (Fig. 12) in the horizontal orientation, the use of a wire grid in either orientation, or other special mounting procedures suitable to the specimen being tested. Fig. 8 shows a wire grid suitable for several types of intumescent specimens. The exact mounting and retaining method used shall be specified in the test report. Additional specialized guidance to the operator is provided in Ref (2).

8.1.4 Assemblies shall be tested as specified in 8.1.2 or 8.1.3 as appropriate. However, where thin materials or composites are used in the fabrication of an assembly, the presence of an air gap or the nature of any underlying construction often significantly affects the ignition and burning characteristics of the exposed surface. The influence of the underlying layers must be understood and care taken to ensure that the test result obtained on any assembly is relevant to its use in practice. When the product is a material or composite that is normally attached to a well defined substrate, it shall be tested in conjunction with that substrate, using the recommended fixing technique, for example, bonded with the appropriate adhesive or mechanically fixed.

8.1.5 Products that are thinner than 6 mm shall be tested with a substrate representative of end use conditions, such that the total specimen thickness is 6 mm or more. In the case of specimens of less than 6 mm in thickness and that are used with an air space adjacent to the unexposed face, the specimens shall be mounted so that there is an air space of at least 12 mm between its unexposed face and the refractory fibre blanket. This is achieved by the use of a metal spacer frame.

8.2 *Conditioning*—Specimens shall be conditioned to moisture equilibrium (constant weight) at an ambient temperature of $23 \pm 3^\circ\text{C}$ and a relative humidity of $50 \pm 5\%$.

9. Test Environment

9.1 The apparatus shall be located in a draft-free environment in an atmosphere of relative humidity of between 20 and 80 % and a temperature between 15 and 30°C .

10. Calibration of Apparatus

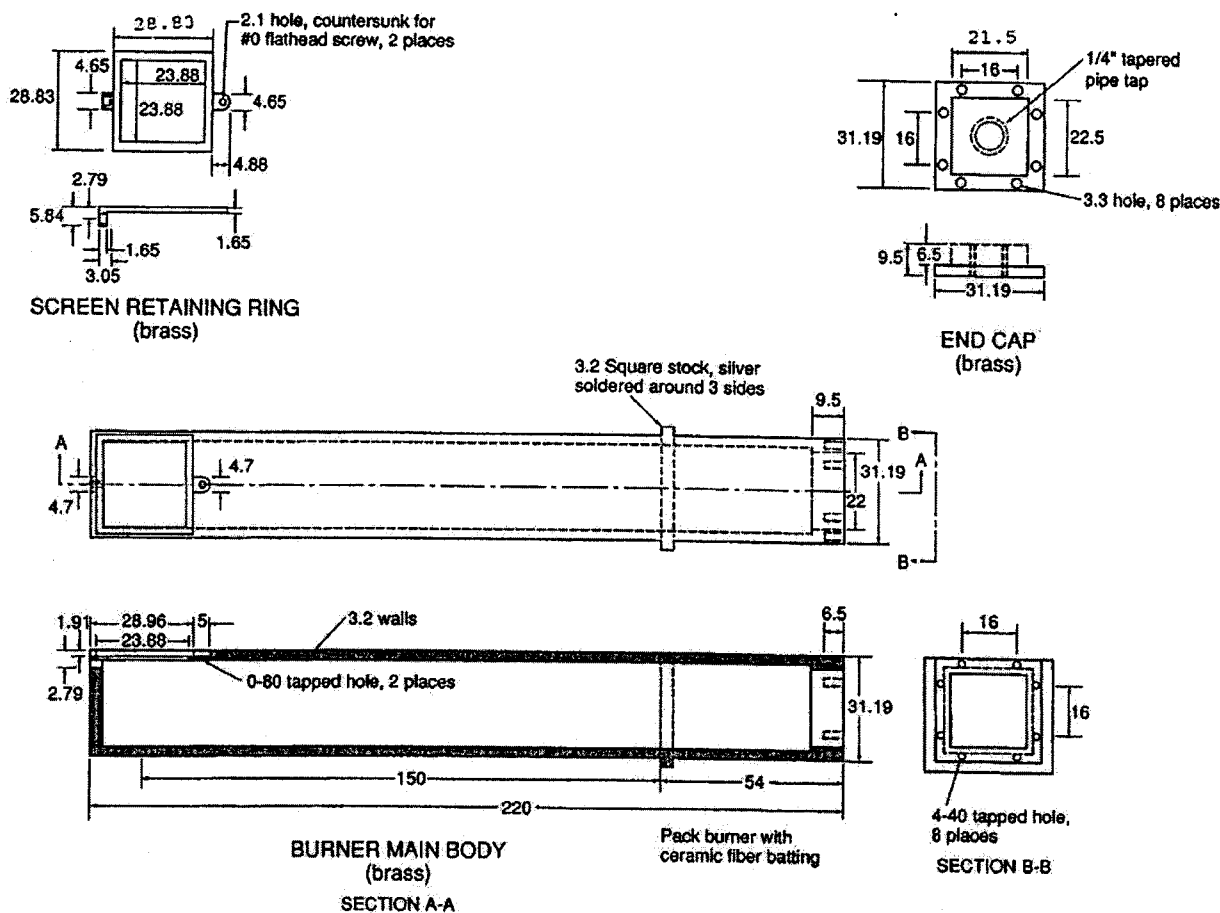
10.1 *Heater Flux Calibration*—Set the temperature controller to the required flux by using the heat fluxmeter at the start of the test day, after changing to a new flux level, or when the cone-heater orientation is changed. Do not use a specimen holder when the heat fluxmeter is inserted into the calibration position. Operate the cone heater for at least 10 min and ensure that the controller is within its proportional band before beginning this calibration.

10.2 Oxygen Analyzer Calibration:

10.2.1 Preliminary Calibrations:

10.2.1.1 The oxygen analyzer delay time must be determined. This is done by arranging for a methane flow rate equivalent to 5 kW to the calibration burner. The heater shall not be turned on for this calibration. Record the output of the analyzer on a strip-chart recorder as the methane supply, turned on and ignited, reaches a steady value, and then returns to baseline after the supply is cut off. Record the temperature for the exhaust-orifice meter at the same time. Determine the turn-on delay as the time difference between the time when the temperature reading reaches 50 % of its ultimate deflection and the time when the oxygen reading reaches 50 % of its ultimate deflection. Determine the turn-off delay similarly at turn-off. Take the delay time as the average of the turn-on delay and turn-off delay. Use this value, t_{L_0} subsequently to time-shift all the oxygen readings.

10.2.1.2 If the oxygen analyzer is equipped with an electric response-time adjustment, set it so that at turn-off there is just



Note 1—All dimensions are in millimetres except where noted.
 FIG. 11 Calibration Burner

a trace of overshoot when switching rapidly between two different calibration gases.

10.2.1.3 The timing of the scans by the data collection system shall be calibrated with a timer accurate to within 1 s in 1 h. The data output shall show event times correct to 3 s.

10.2.2 *Operating Calibrations*—At the start of testing each day, the oxygen analyzer shall be zeroed and calibrated. For zeroing, the analyzer shall be fed with nitrogen gas with the same flow rate and pressure as for the sample gases. Calibration shall be similarly achieved using ambient air and adjusting for a response of 20.95%. Analyzer flow rates shall be carefully monitored and set to be equal to the flow rate used when testing specimens. After each specimen has been tested, ensure that a response level of 20.95% is obtained using ambient air.

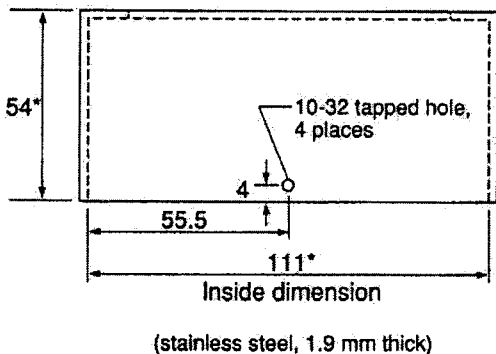
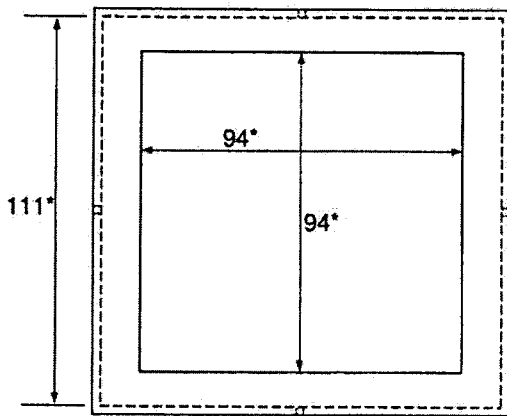
10.3 *Heat Release Rate Calibration:*

10.3.1 The heat release calibration shall be performed at the start of testing each day. Methane (purity of at least 99.5%) shall be introduced into the calibration burner at a flow rate corresponding to 5 kW based on the net heat of combustion of methane ($50.0 \times 10^3 \text{ kJ/kg}$) using a precalibrated flowmeter.

The flowmeter used shall be one of the following: a dry test meter, a wet test meter, or an electronic mass flow controller. If an electronic mass-flow controller is used, it shall be calibrated periodically against a dry test meter or a wet test meter. The test meter shall be equipped with devices to measure the temperature and pressure of the flowing gas, so that appropriate corrections to the reading may be made. If a wet test meter is used, the readings shall also be corrected for the moisture content. The exhaust fan shall be set to the speed to be used for subsequent testing. The required calculations are given in Section 13.

Note 2—It shall be permitted for calibration to be performed with the cone heater operating or not, but calibration shall not be performed during heater warm up.

10.4 *Load Cell Calibration*—The load cell shall be calibrated with standard weights in the range of test specimen weight each day of testing or when the load cell mechanical zero needs to be adjusted. Adjust the load cell mechanical zero if necessary due to different specimen holder tare weights after changing orientation.



NOTE 1—All dimensions are in millimetres.
NOTE 2—* Indicates a critical dimension.

FIG. 12 Optional Retainer Frame for Horizontal Orientation Testing

10.5 *Smoke Meter Calibration*—The smoke meter is initially calibrated to read correctly for two different value neutral density filters, and also at 100 % transmission. Once this calibration is set, only the zero value of extinction coefficient (100 % transmission) normally needs to be verified prior to each test.

11. Procedure

11.1 Preparation:

11.1.1 Check the CO₂ trap and the final moisture trap. Replace the sorbents if necessary. Drain any accumulated water in the cold trap separation chamber. Normal operating temperature of the cold trap shall be the lowest temperature at which trap freezing does not occur (approximately 0°C).

NOTE 3—If any of the traps or filters in the gas sampling line have been opened during the check, the gas sampling system shall be checked for leaks, for example, by introducing pure nitrogen, at the same flow rate and pressure as for the sample gases, from a nitrogen source connected as close as possible to the ring sampler. The oxygen analyzer must then read zero.

11.1.2 Turn on power to the cone heater and the exhaust blower. (Power to the oxygen analyzer, load cell, and pressure transducer is not to be turned off on a daily basis.)

11.1.3 Set an exhaust flow rate of 0.024 ± 0.002 m³/s. (Under room temperature conditions this corresponds to approximately 30 g/s.)

11.1.4 Perform the required calibration procedures specified in Section 9. In the horizontal orientation, put an empty specimen holder (with refractory blanket) in place during warmup and in between tests to avoid excessive heat transmission to the load cell.

11.1.5 If external ignition is used, position the spark plug holder in the location appropriate to the orientation being used.

11.2 Procedure:

11.2.1 When ready to test, if testing in the horizontal orientation, first remove the empty specimen holder.

NOTE 4—When testing in the vertical orientation, the use of an empty specimen holder is not necessary.

11.2.2 Insert the radiation shield and position the specimen, in the appropriate holder, in place. The holder must be at room temperature initially.

11.2.3 Leave the radiation shield in place for a sufficient time to ensure stability of operation (load cell equilibrium), but for no longer than 10 s if the shield is not water cooled. Initiate data collection upon removal of the radiation shield, which signifies the start of the test. The data collection intervals shall be 5 s or less.

11.2.4 Place the specimen, held in the appropriate holder, in place and start the data collection. The data collection intervals shall be 5 s or less. (The holder must be at room temperature initially.)

11.2.5 Start the ignition timer if external ignition is to be used. Move the spark plug into place and turn on spark power.

11.2.6 Record the times when flashing or transitory flaming occur; when sustained flaming occurs, record the time, turn off the spark, and remove the spark igniter. If the flame extinguishes in less than 60 s after turning off the spark, reinsert the spark igniter and turn on the spark. If flaming recurs, stop the test, discard the test data, and repeat the test without removing the spark until the entire test is completed. Report these events in the test report.

NOTE 5—For reporting the time of sustained flaming, the time to be reported is when the flaming was initially observed, not when the 4 s period elapsed.

11.2.7 Collect data until 2 min after any flaming or other signs of combustion cease, the average mass loss over a 1-min period has dropped below 150 g/m², or until 60 min have elapsed.

11.2.8 Remove specimen holder.

11.2.9 For testing in the horizontal orientation, replace the empty specimen holder.

11.2.10 If the specimen does not ignite in 30 min, remove and discard, unless the specimen is showing signs of heat evolution.

NOTE 6—Stop testing if explosive spalling or excessive swelling occur. The procedures described in 8.1 may be useful in mitigating these effects.

11.2.11 Unless otherwise specified in the material or performance standard, make three determinations and report as specified in Section 14. The 180-s mean heat release rate readings (as specified in Section 14) shall be compared for the three specimens. If any of these mean readings differ by more than 10 % from the average of the three readings, then a further set of three specimens shall be tested. In such cases, report the averages for the set of six readings.

12. Test Limitations

12.1 The test data have limited validity if any of the following occur:

12.1.1 In vertical test orientation, the specimen melts sufficiently to overflow the melt trough,

12.1.2 Explosive spalling occurs, or

12.1.3 The specimen swells sufficiently prior to ignition to touch the spark plug or swells up to the plane of the heater base plate during combustion.

13. Calculation

13.1 *General*—The equations in this section assume only oxygen is measured, as indicated on the gas analysis system in Fig. 9. Appropriate equations that can be used for cases where additional gas analysis equipment (CO₂, CO, water vapor) is used are given in Annex A1. If a CO₂ analyzer is used and CO₂ is not removed from the oxygen sampling lines, the equations in Annex A1 must be used.

13.2 *Calibration Constant Using Methane*—Perform the methane calibration daily to check for the proper operation of the instrument and to compensate for minor changes in mass flow determination. (A calibration more than 5 % different from the previous one is not normal and suggests instrument malfunction.) Compute this calibration constant, C, from the basic heat release equation (Eq 1) or from Eq 2.

$$5.0 = (12.54 \times 10^3) (1.10) C \sqrt{\frac{\Delta P}{T_c}} \frac{(X_{O_2}^0 - X_{O_2})}{1.105 - 1.5 X_{O_2}} \quad (1)$$

Solved for C, this gives

$$C = \frac{5.0}{1.10 (12.54 \times 10^3)} \sqrt{\frac{T_c}{\Delta P}} \frac{1.105 - 1.5 X_{O_2}}{X_{O_2}^0 - X_{O_2}} \quad (2)$$

where 5.0 corresponds to 5.0 kW methane supplied, 12.54 × 10³ is Δh_c/r_c for methane, 1.10 is the ratio of oxygen to air molecular weights, and the variables are given in 3.1. The derivation of the basic Eq 1 is given in Refs (3) and (4).

13.3 *Calculations for Test Specimen*—The following calculations are generally necessary for various applications. The relevant material or performance standard may prescribe additional calculations.

13.3.1 Heat Release:

13.3.1.1 Prior to performing other calculations, the oxygen analyzer time shift is incorporated by the following equation:

$$X_{O_2}(t) = X_{O_2}^1(t + t_0) \quad (3)$$

13.3.1.2 Then determine the heat-release rate by the following equation:

$$\dot{Q}(t) = \left(\frac{\Delta h_c}{r_c}\right) (1.10) C \sqrt{\frac{\Delta P}{T_c}} \frac{(X_{O_2}^0 - X_{O_2}(t))}{1.105 - 1.5 X_{O_2}(t)} \quad (4)$$

13.3.1.3 Set the value of (Δh_c/r_c) for the test specimen equal to 13.1 × 10³ kJ/kg unless a more exact value is known for the test material. Determine the heat-release rate per unit area as follows:

$$\dot{q}''(t) = \frac{\dot{Q}(t)}{A_s} \quad (5)$$

where A_s is the initially exposed area, that is, 0.0088 m² in the vertical orientation and in the horizontal orientation if the retainer frame is used, and 0.01 m² in the horizontal orientation if the retainer frame is not used.

13.3.1.4 Determine the total heat released during combustion, q^{*}, by summation as follows:

$$q^* = \sum_i \dot{q}''_i(t) \Delta t \quad (6)$$

where the summation begins at the next reading after the last negative rate of heat release reading occurred at the beginning of the test, and continuing until the final reading recorded for the test.

13.3.2 *Mass-Loss Rate and Effective Heat of Combustion*—Compute the required mass-loss rate, -dm/dt, at each time interval using five-point numerical differentiation. The equations to be used are as follows:

13.3.2.1 For the first scan (i = 0):

$$-\left[\frac{dm}{dt}\right]_{i=0} = \frac{25m_0 - 48m_1 + 36m_2 - 16m_3 + 3m_4}{12\Delta t} \quad (7)$$

13.3.2.2 For the second scan (i = 1):

$$-\left[\frac{dm}{dt}\right]_{i=1} = \frac{3m_0 + 10m_1 - 18m_2 + 6m_3 - m_4}{12\Delta t} \quad (8)$$

13.3.2.3 For any scan for which 1 < i < n - 1 (where n = total number of scans):

$$-\left[\frac{dm}{dt}\right]_i = \frac{-m_{i-2} + 8m_{i-1} - 8m_{i+1} + m_{i+2}}{12\Delta t} \quad (9)$$

13.3.2.4 For the last scan but one (i = n - 1):

$$-\left[\frac{dm}{dt}\right]_{i=n-1} = \frac{-3m_n - 10m_{n-1} + 18m_{n-2} - 6m_{n-3} + m_{n-4}}{12\Delta t} \quad (10)$$

13.3.2.5 For the last scan (i = n):

$$-\left[\frac{dm}{dt}\right]_{i=n} = \frac{-25m_n + 48m_{n-1} - 36m_{n-2} + 16m_{n-3} - 3m_{n-4}}{12\Delta t} \quad (11)$$

13.3.2.6 Determine the average effective heat of combustion as follows:

$$\Delta h_{c,eff} = \frac{\sum_i \dot{Q}_i(t) \Delta t}{m_i - m_f} \quad (12)$$

with the summation taken over the entire test length. A time-varying value is also determined as follows:

$$\Delta h_{c,eff}(t) = \frac{\dot{Q}_i(t)}{-(dm/dt)} \quad (13)$$

13.3.3 Smoke Obscuration:

13.3.3.1 Determine the extinction coefficient, k, by the smoke meter electronics as follows:

$$k = \left(\frac{1}{T}\right) \ln \frac{I_0}{I_f} \quad (14)$$

13.3.3.2 The average specific extinction area obtained during the test is given as follows:

$$\sigma_{(Avg)} = \frac{\sum_i k_i \Delta t_i}{m_i - m_f} \quad (15)$$

14. Report

14.1 Report the following information unless specified otherwise in the relevant material or performance standard. Clearly state the units for all measurements in the report. Certain units convenient for reporting are suggested in parentheses.

- 14.1.1 Specimen identification code or number.
- 14.1.2 Manufacturer or submitter.
- 14.1.3 Date of test.
- 14.1.4 Operator.
- 14.1.5 Composition or generic identification.
- 14.1.6 Specimen thickness.⁶
- 14.1.7 Specimen mass.⁶
- 14.1.8 Color of the specimens.
- 14.1.9 Details of specimen preparation by the testing laboratory.

14.1.10 Test orientation, specimen mounting, and whether the retainer frame, the wire grid, or other special mounting procedures were used.

14.1.11 Heating flux and exhaust system flow rate.⁶

14.1.12 Number of replicate specimens tested under the same conditions. (This shall be a minimum of three, except for exploratory testing.)

14.1.13 Time to sustained flaming (seconds).⁶ If sustained flaming was not observed, record that there was no ignition.

14.1.14 Heat-release rate (per unit area) curve (kW/m²).⁶

14.1.15 Peak \dot{q}'' , and average \dot{q}'' values for the first 60, 180, and 300 s after ignition, or for other appropriate periods (kW/m²).⁵ For specimens that do not show sustained flaming, report the above quantities tabulated for periods beginning with the next reading after the last negative rate of heat release reading at the beginning of the test.

Note 7—Average rate of heat release values are to be calculated using the trapezium rule for integration. For example, with a 5 s data collection interval, \dot{q}''_{180} is obtained as follows: (1) Sum up all rate of heat release values at the second through thirty-sixth scan after ignition or the last negative value (if the test is completed before the 180 s period is elapsed, use the test average instead); (2) Add half of the rate of heat release measured at the first scan and at the thirty-seventh scan after ignition or after the last negative value; (3) Multiply the sum obtained in (2) by the scan interval (5 s) and divide it by 180.

14.1.16 Total heat released by the specimen (MJ/m²) as determined in 12.3.1.4.⁶

14.1.17 Average $\Delta h_{c,eff}$ for entire test (MJ/kg).⁶

14.1.18 Curve of $\Delta h_{c,eff}$ (MJ/kg) (optional).⁶

14.1.19 Mass remaining after test (g).⁶

14.1.20 Sample mass loss (kg/m²).⁸ The average specimen mass loss rate (g/m²-s), computed over the period starting

when 10 % of the ultimate specimen mass loss occurred and ending at the time when 90 % of the ultimate specimen mass loss occurred.

14.1.21 Smoke obscuration. Report the average specific extinction area (m²/kg).⁶

14.1.22 Values determined in 14.1.13, 14.1.15, 14.1.17, and 14.1.21, averaged for all specimens.

14.1.23 Additional observations (including times of transitory flaming or flashing), if any.⁶

14.1.24 Difficulties encountered in testing, if any.⁶

15. Precision and Bias⁷

15.1 Precision:

15.1.1 Interlaboratory trials were conducted by Committee E05 to determine the repeatability and reproducibility of this test method. The results were analyzed in conjunction with the results of a parallel set of inter-laboratory trials sponsored by the International Organization for Standardization (ISO). The complete results have been placed on file at ASTM headquarters as a Research Report. The results obtained for repeatability and reproducibility are given below; further details of the interlaboratory trials are given in Appendix X2.

15.1.2 The following definitions of repeatability (r) and reproducibility (R) are used:

$$r = f\sqrt{2} \sigma_r \quad (16)$$

$$R = f\sqrt{2} \sigma_R \quad (17)$$

where σ_r is the repeatability standard deviation, σ_R is the reproducibility standard deviation, the coefficient $\sqrt{2}$ is derived from the fact that r and R refer to the difference between two single test results, and f , which is approximately 2, corresponds to the probability level of 95 % being taken. This product is then rounded off:

$$r = 2.8 s_r \quad (18)$$

$$R = 2.8 s_R \quad (19)$$

For calculations, the sample-based standard deviation estimates, s , are substituted for the population standard deviations, σ , since the latter are not known.

15.1.3 For the materials tested, values for repeatability r and reproducibility R have been calculated for six variables. These variables, chosen as being representative for the test results are: t_{ig} , \dot{q}''_{max} , \dot{q}''_{180} , \dot{q}''_{100} , $\Delta h_{c,eff}$, and σ_r . A linear regression model was used to describe r and R as a function of the mean over all replicates and over all laboratories for each of the six variables. The regression equations are given below. The range of mean values over which the fit was obtained is also indicated. The results for time to sustained flaming, t_{ig} , in the range of 5 to 150 s were:

$$r = 4.1 + 0.125 t_{ig} \quad (20)$$

$$R = 7.4 + 0.220 t_{ig} \quad (21)$$

The results for peak heat release rate, \dot{q}''_{max} , in the range of 70 to 1120 kW/m² were:

$$r = 13.3 + 0.131 \dot{q}''_{max} \quad (22)$$

⁶ Report these items for each specimen.

⁷ Supporting data are available from ASTM Headquarters. Request RR: E05-1008.

$$R = 60.4 + 0.141 \dot{q}[Prime]_{max} \quad (23)$$

The results for 180-s average heat release rate, \dot{q}''_{180} , in the range of 70 to 870 kW/m² were:

$$r = 23.3 + 0.037 \dot{q}[Prime]_{180} \quad (24)$$

$$R = 25.5 + 0.151 \dot{q}[Prime]_{180} \quad (25)$$

The results for total heat released, \dot{q}''_{tot} , in the range of 5 to 720 MJ/m² were:

$$r = 7.4 + 0.068 \dot{q}[Prime]_{tot} \quad (26)$$

$$R = 11.8 + 0.088 \dot{q}[Prime]_{tot} \quad (27)$$

The results for effective heat of combustion, $\Delta h_{c,eff}$, in the range of 7 to 40 kJ/g were:

$$r = 1.23 + 0.050 \Delta h_{c,eff} \quad (28)$$

$$R = 2.42 + 0.055 \Delta h_{c,eff} \quad (29)$$

The results for average specific extinction area, σ_f , in the range of 30 to 2200 m²/kg were:

$$r = 59 + 0.076 \sigma_f \quad (30)$$

$$R = 63 + 0.215 \sigma_f \quad (31)$$

15.2 *Bias*—For solid specimens of unknown chemical composition, as used in building materials, furnishings, and common occupant fuel load, it has been documented that the use of the oxygen consumption standard value of $\Delta h_c/r_o = 13.1 \times 10^3$ kJ/kg oxygen results in an expected error band of $\pm 5\%$ compared to true value (1). For homogeneous materials with only a single pyrolysis mechanism, this uncertainty can be reduced by determining Δh_c from oxygen bomb measurements and r_o from ultimate elemental analysis. For most testing, this is not practical since specimens may be composite and nonhomogeneous, and may exhibit several degradation reactions. Therefore, for unknown samples a $\pm 5\%$ accuracy limit is seen. For reference materials, however, careful determination of $\Delta h_c/r_o$ can make this source of uncertainty substantially less.

16. Keywords

16.1 cone calorimeter; heat—heat release rate; ignitability—radiant ignition; mass—mass loss rate; oxygen consumption method—heat release rate; smoke

ANNEX

(Mandatory Information)

A1. CALCULATION OF HEAT RELEASE WITH ADDITIONAL GAS ANALYSIS

A1.1 Introduction

A1.1.1 The equations to calculate heat release rate in Section 12 assume CO₂ is removed from the gas sample in a chemical scrubber before oxygen is measured, as indicated in Fig. 9. Some laboratories are equipped to measure CO₂; in that case it is not necessary to remove the CO₂ from the oxygen line. The advantage, in that case, is that it is possible to avoid the chemical scrubbing agent, which is costly and requires careful handling.

A1.1.2 In this annex equations are given that are to be used when CO₂ is measured but not scrubbed out of the sampling lines. Two cases are considered. In the first case, part of the dried and filtered sample stream is diverted into infrared CO₂ and CO analyzers (see option in Fig. 9). In the second case, a water-vapor analyzer is also added. To avoid condensation, the measuring of water vapor concentration in the flow of combustion products requires a separate sampling system with heated filters, heated sampling lines, and a heated analyzer.

A1.2 Symbols

A1.2.1 The following symbols are used in this annex.

M_a	= molecular weight of air (kg/kmol).
M_c	= molecular weight of the combustion products (kg/kmol).
\dot{m}_f	= exhaust duct mass flow rate (kg/s).
$t_{d,2}$	= delay time of the CO ₂ analyzer(s).
$t_{d,3}$	= delay time of the CO analyzer(s).
$t_{d,4}$	= delay time of the water vapor analyzer(s).

X_{CO_0}	= initial CO ₂ reading, mole fraction (-).
X_{CO}	= initial CO reading, mole fraction (-).
$X_{H_2O}^0$	= initial water vapor reading, mole fraction (-).
$X_{O_2}^a$	= ambient oxygen mole fraction (-).
$X_{CO_2}^1$	= CO ₂ reading before delay time correction, mole fraction (-).
X_{CO}^1	= CO reading before delay time correction, mole fraction (-).
$X_{H_2O}^1$	= water vapor reading before delay time correction, mole fraction (-).
X_{CO_2}	= CO ₂ reading after delay time correction, mole fraction (-).
X_{CO}	= CO reading after delay time correction, mole fraction (-).
X_{H_2O}	= water reading after delay time correction, mole fraction (-).
ϕ	= oxygen depletion factor (-).

A1.3 References

A1.3.1 Eq A1.5, Eq A1.6, and Eq A1.10 are derived in Ref (3).

A1.4 Case Where CO₂ and CO are Also Measured

A1.4.1 Just as for the oxygen analyzer, measurements of CO₂ and CO shall be time shifted to take transport time in the sampling lines into account as follows:

$$X_{O_2}(t) = X_{O_2}(t + t_d) \quad (A1.1)$$

$$X_{CO_2}(t) = X_{CO_2}(t + t_{d,2}) \quad (A1.2)$$

$$X_{CO}(t) = X_{CO}^1(t + t_{d,3}) \quad (A1.3)$$

Here, the delay times t_d^1 and t_d^2 for the CO₂ and CO analyzers respectively are usually different (smaller) than the delay time t_d for the oxygen (O₂) analyzer.

A1.4.2 The exhaust duct flow is as follows:

$$\dot{m}_e = C \sqrt{\frac{\Delta P}{T_c}} \quad (A1.4)$$

A1.4.3 The rate of heat release shall in that case be determined as follows:

$$\dot{q} = 1.10 \left(\frac{\Delta h_c}{r_a} \right) X_{O_2} \left[\frac{\phi - 0.172(1 - \phi) X_{CO} / X_{O_2}}{(1 - \phi) + 1.105 \phi} \right] \dot{m}_e \quad (A1.5)$$

A1.4.4 The oxygen depletion factor, ϕ , is calculated as follows:

$$\phi = \frac{X_{O_2}(1 - X_{CO_2} - X_{CO}) - X_{O_2}(1 - X_{CO_2})}{X_{O_2}(1 - X_{CO_2} - X_{CO}) - X_{O_2}} \quad (A1.6)$$

A1.4.5 The ambient mole fraction of oxygen (O₂) is as follows:

$$X_{O_2} = (1 - X_{H_2O}) X_{O_2}^0 \quad (A1.7)$$

A1.4.6 The second term in the numerator of the factor in brackets in Eq A1.5 is a correction for incomplete combustion of some carbon to CO instead of CO₂. In fact, X_{CO} is usually very small, shall be permitted to be neglected in Eq A1.5 and Eq A1.6. The practical implication of this is that a CO analyzer will generally not result in a noticeable increase in accuracy of heat release rate measurements. Consequently Eq A1.5 and Eq A1.6 shall be permitted to be used even if no CO analyzer is present, by setting $X_{CO} = 0$.

A1.5 Case Where Water Vapor is Also Measured

A1.5.1 In an open combustion system, such as that used in this test method, the flow rate of air entering the system cannot be measured directly but is inferred from the flow rate measured in the exhaust duct. An assumption is required

regarding the expansion due to combustion of the fraction of the air that is fully depleted of its oxygen. This expansion depends on the composition of the fuel and the actual stoichiometry of the combustion. A suitable average value for the volumetric expansion factor is 1.105, which is correct for methane.

A1.5.2 This number is already incorporated within Eq 3 and Eq A1.5 for \dot{q} . For cone calorimeter tests it is reasonable to assume that the exhaust gases consist primarily of nitrogen, oxygen, CO₂, water vapor, and CO; thus, measurements of these gases shall be permitted to be used to determine the actual expansion. (It is assumed that the measurements of oxygen, CO₂, and CO refer to a dry gas stream, while the water vapor measurement is with respect to total stream flow.) The mass flow rate in the exhaust duct is then more accurately given by the following equation:

$$\dot{m}_e = \sqrt{M_e M_a} C \sqrt{\frac{\Delta P}{T_c}} \quad (A1.8)$$

A1.5.2.1 The molecular weight M_e of the exhaust gases follows from:

$$M_e = [4.5 + (1 - X_{H_2O})(2.5 + X_{O_2} + 4X_{CO_2})] \times 4 \quad (A1.9)$$

A1.5.2.2 Then taking M_a as 28.97, the heat release rate is given as follows:

$$\dot{q} = 1.10 \left(\frac{\Delta h_c}{r_a} \right) (1 - X_{H_2O}) X_{O_2}^0 \left[\phi - 0.172(1 - \phi) \left(\frac{X_{CO}}{X_{O_2}} \right) \right] \quad (A1.10)$$

$$\left[\frac{1 - X_{O_2} - X_{CO_2} - X_{CO}}{1 - X_{O_2} - X_{CO_2}} \right] \dot{m}_e$$

A1.5.3 The water vapor readings used in Eq A1.10 are time shifted in a similar way as in Eq A1.1-A1.3 for the other analyzers as follows:

$$X_{H_2O}^0(t) = X_{H_2O}^0(t + t_d^3) \quad (A1.11)$$

APPENDICES

(Nonmandatory Information)

X1. COMMENTARY

X1.1 Introduction

X1.1.1 This commentary is provided (1) to give some insight into the development of the test method, (2) to describe the rationale for the design of various features of the apparatus, and (3) to describe the use of the data.

X1.2 Rate of Heat Release Rate Measurements

X1.2.1 The rate of heat release is one of the most important variables, in many cases the single most important variable, in determining the hazard from a fire (4). This rate of heat release is the total rate, as a function of time. With many items composed of many surfaces contributing to the fire, its evaluation is quite complex. For each separate surface it must first be

determined when, if at all, it will become ignited. The size of the fire from any already burning items must be known, since that constitutes the external irradiance to nearby items. Next, the flame spread over the surface in question must be evaluated. The rate of heat release from the whole surface can be evaluated knowing the rate of heat release per unit area for a given irradiance, as a function of time. This last quantity is the only one that can be measured in a bench-scale test. The total fire output involves a summation over all surfaces. Also to be considered is the fact that some elements may burn out and then no longer contribute to the fire. This procedure is conceptually straightforward but can be very cumbersome to compute.

X1.2.2 Many common combustibles do not have the geometrically simple surfaces required to make computations of this kind. Other complications, such as melting, dripping, or collapsing, can also preclude a detailed mathematical analysis. In such cases a simpler, more empirical model is appropriate. An example of the use of bench-scale heat release rate measurements in deriving a fire hazard assessment is available (5).

X1.2.3 This test method does not prescribe the irradiance levels, nor whether external ignition is to be used. These must be determined separately for each product class. For a given class of applications and products, a comparison with some full-scale fires is generally necessary to determine the time period over which the heat release rate is to be calculated. A material or performance standard can then be developed for that product category that may contain further guidance and limitations for testing. For exploratory testing, it is initially recommended to use the horizontal orientation and an irradiance value of 35 kW/m²; in the absence of further specifications from the sponsor, tests at 25, 35, and 50 kW/m² are recommended.

X1.2.3.1 The standard specimen orientation for testing is horizontal. This is applicable even to specimens, such as wall linings, where the end-use orientation of the product is vertical. The reason is that this test method does not represent a scale model of the full-scale product. Instead, the fundamental response of a specimen to specified external irradiance is tested. The total heating to the specimen is the sum of the external irradiance plus the heat flux from the specimen's own flame. The heat flux from the specimen's flames will be different in the two orientations. What must be borne in mind is that there is no fixed relationship between this flame flux for the bench-scale specimen compared to the full-scale product. Instead, the relationship varies in accordance with product application, as explained in X1.2.3. The relationship between the bench-scale heat release rate and the one in full-scale must establish a test irradiance value that correctly accounts for the fact that the full-scale product is exposed to a different flame flux than the bench-scale specimen.

X1.2.3.2 The standard testing orientation is horizontal since, for most types of specimens, there are significantly fewer experimental problems due to specimen melting, dripping, or falling out. Reproducibility of ignition data is also better in this orientation, due to a wider column of pyrolysates present at the location of the spark gap. The vertical orientation is made available because in certain diagnostic studies it is more feasible to install optical pyrometers, specimen thermocouples, and other specialized instrumentation in that orientation.

X1.2.3.3 The test results may not be statistically significant unless the irradiance used is substantially (5 to 10 kW/m²) higher than the minimum irradiance level needed for sustained flaming to occur for that specimen.

X1.3 Choice of Operating Principle

X1.3.1 A number of apparatus have been developed over the years for measuring rate of heat release; most of these have been reviewed in detail (6). Traditionally, the simplest measurement scheme is a direct measurement of flow enthalpy from a chamber thermally lagged to present an adiabatic

environment. A truly adiabatic apparatus, with the use of guard heaters, would be possible but would also be prohibitively expensive and has not been implemented. A combustion chamber insulated in a simpler manner leads to a significant under measurement of the heat release, so only an empirical calibration is possible. An example of an insulated chamber method is Test Method E 906. Furthermore, that calibration may be sensitive to the radiant fraction (or sootiness) of the combustible (7, 8). A more advanced scheme is an isothermal instrument, rather than an adiabatic one, with the heat-release rate taken to be the fuel which must be supplied by a substitution burner to maintain isothermal conditions (9). This scheme gives better results, since only second-order heat loss error terms remain; however, its practical implementation is complex and costly.

X1.3.2 It can be concluded that it is difficult to measure heat directly without losing some of it. However, it is simple to capture all combustion products without losing any and to measure the oxygen levels in that stream. Heat release can be computed from such measurements with the availability of the oxygen-consumption principle (1). This principle states that for most common combustibles an amount of heat equal to 13.1×10 kJ is released for each kilogram of oxygen consumed from the air stream. This constant varies $\pm 5\%$ for most common combustibles; certain exceptions are given in Ref (1). The method remains useful even if a significant fraction of the products become CO or soot, rather than CO₂; in these cases, correction terms are known (1, 3) and can be applied. A typical case of less than 2% error has been determined to result for cellulose producing 10% incomplete combustion going to CO (1). Note that excessively high CO-production values, which could result from restricted oxygen supply, cannot result in the calorimeter used in this test method since oxygen intake is not restricted. By adopting the oxygen consumption principle as the method of measurement, it becomes possible to design an apparatus of significantly improved precision but without excessive complexity. Since heat measurements are not required, the apparatus does not need thermal insulation.

X1.4 Heater Design

X1.4.1 Experience with various rate-of-heat-release measurement techniques suggests that for minimal errors in irradiance, the specimen should see only (1) a thermostatically controlled heater, (2) a water-cooled plate, or (3) open air. Nearby solid surfaces, if they are not temperature-controlled, can rise in temperature due to specimen flame heating and then act as further sources of radiation back to the specimen. Further, when oxygen consumption is used as the measurement principle, a gas-fired heater is not desirable because it can contribute a noisy baseline to the oxygen readings, even though it can be subtracted out in steady state.

X1.4.2 A heater in the shape of a truncated cone was first explored for use in an ignitability apparatus by the International Organization for Standardization (ISO) (see ISO 5657-1986). The heater adopted in the present method is similar, but not identical to the ISO one. The main differences include higher heat fluxes, temperature control, and more rugged design details. In the horizontal orientation, the conical shape approximately follows the fire plume contours while the central

hole allows the stream to emerge without impacting on the heater. A thin layer of cool air is pulled along, and the flames do not attach to the sides of the cone. The central hole has a further function: in its absence the middle of the specimen would receive a higher irradiance than the edges. With the hole, the irradiance is uniform to within $\pm 2\%$. In the vertical orientation, the hole still serves the purpose of providing radiation uniformity; although because of the presence of a natural convection boundary layer, the deviations are higher (from ± 5 to $\pm 10\%$) (10).

X1.5 Pilot Ignition

X1.5.1 Ignition of test specimens in many apparatus is achieved by a gas pilot. This tends to have numerous difficulties—sooting, deterioration of orifices, and contribution to the heat release rate. It is difficult to design a pilot that can be centrally located over the specimen, is resistant to blowout, and yet does not apply an additional heating flux to the specimen. (A point of elevated heating on the specimen makes it difficult to analyze mathematically the response of the specimen.) An electric spark is free of most of these difficulties, requiring only an occasional cleaning and adjustment of the electrodes. For these reasons, an electric spark ignition was adopted.

X1.6 Back Face Conditions

X1.6.1 The heat losses through the specimen back face can have an influence on the burning rate near the end of its burning time. For reproducible measurements, the losses through the back face should be standardized. The simplest theoretical boundary conditions—an adiabatic boundary or an isothermal one at ambient temperature—are not achievable. However, a reasonable approximation to the former can be made by using a layer of an insulating material. This is easier to do for the horizontal orientation case, in which case a very low density refractory blanket is used. In the vertical orientation some structural rigidity of the backing is desired; consequently, a layer of higher density backing may be necessary.

X1.7 Oxygen Analyzer

X1.7.1 The analyzer should be of the paramagnetic type, with baseline noise and short-term drift of approximately ± 50 ppm oxygen. Other types of analyzers (electrochemical and catalytic) generally cannot meet this requirement. Paramagnetic analyzers also exhibit an intrinsically linear response. The linearity is normally better than can be determined with $\pm 0.1\%$ oxygen gas mixtures. Since an oxygen analyzer is sensitive to stream pressures, either the readings have to be compensated with an absolute pressure transducer, connected to the analyzer, or the pressure has to be mechanically regulated both against flow fluctuations and atmospheric pressure variations. The analyzer and the pressure regulating or measuring devices must be located in a constant temperature environment to avoid flow errors.

X1.8 Limits to Resolution

X1.8.1 Methane calibration studies (10) showed typical fluctuations of $\pm 1.5\%$, with a linearity to within 5% over the range of 1 to 12 kW, and within 2% over the range of 5 to 12

kW. Calibrations with other gases show similar results. Calibration gases can be delivered to the burner in a highly steady manner. The uniformity of solid-fuels combustion, however, is governed by the pyrolysis at the surface, which can under some circumstances show substantial fluctuations. For instance, the fluctuations for polymethylmethacrylate are greater than for red oak (10). Burning thermoplastic specimens occasionally eject individual molten streamers. With solid materials then, the limits to resolution can be expected to be set by the specimen pyrolysis process, rather than by instrument limits.

X1.8.2 The limits to the speed of response of any heat release rate technique are set by the slowest responding element. In the case of the present method, this is the oxygen analyzer, which typically shows a 10 to 90 % response time of 6.9 s. Response times of the pressure transducer and thermocouple can be much faster. They should be set to be only somewhat faster, however, to avoid introducing instrument noise without increasing resolution.

X1.9 Effective Heat of Combustion

X1.9.1 The effective heat of combustion is a constant during combustion of homogeneous specimens having only a single mode of degradation and is less than the value of the theoretical net heat of combustion. Examples of a material with a single mode of degradation and, therefore, a constant effective heat of combustion include most organic liquids. Cellulosic products, by contrast, typically show more than one mode of degradation and a varying effective heat of combustion. For materials having more than one mode of degradation, or for composites or nonhomogeneous materials, the effective heat of combustion is not necessarily constant.

X1.10 Smoke Obscuration Measurements

X1.10.1 The smoke measurement system is different from that used in Test Method E 662 for the following reasons:

X1.10.1.1 Simultaneous mass measurements are available,

X1.10.1.2 Irradiances up to 100 kW/m^2 are available,

X1.10.1.3 The combustion takes place in a flow stream, not in a closed box, and

X1.10.1.4 A monochromatic light source is used.

X1.10.2 Accurate measurement of smoke obscuration requires, among other considerations, the following:

X1.10.2.1 A highly collimated light source, insensitive to stray light,

X1.10.2.2 Measurement in a well mixed unstratified stream,

X1.10.2.3 A high degree of stability against drift due to voltage fluctuations, source aging, thermal effects, etc., and

X1.10.2.4 The ability to make extended measurements without error due to progressive coating of optics by soot.

X1.10.3 In addition, it is desirable to select a monochromatic source (11), preferably in the red portion of the spectrum, for ease of interpreting the data in accordance with the theoretical models. For convenience, it is also desirable to provide direct electric output in logarithmic units to avoid the need for manual range switching or resulting inaccuracies at the high end of the scale. An instrument has been designed that is intended to meet all these requirements (Fig. 11) (12).

Additional construction details are given in construction drawings.⁸ The theory for data analysis is from Refs (13) and (14).

X1.11 Specimen Mounting Methods

X1.11.1 This test method is a general method suitable for testing different types of products and materials. In the simplest case, the product or material is cut out to the correct size, wrapped in aluminum foil, and placed in the horizontal or vertical specimen holder. In many cases, however, the specimen, when heated, may warp, intumesce, delaminate, or burn in an unrepresentative manner along its side edges. Two common procedures for handling such specimens are described in this test method: an edge frame (pertinent only to horizontal orientation testing) and a wire grid (either orientation). These are not the only specimen mounting methods available to the

⁸ Construction drawings for the Cone Calorimeter are available from the Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899.

testing laboratory. Reference (2) suggests some additional procedures. For more unusual specimen types, the testing laboratory will have to devise appropriate mounting methods. Since different mounting methods may give different test results, the method used must be documented in the test report, as mandated in 14.1.10. Since test results are inevitably affected by such mounting devices, they should not be used unless prior testing indicates they are necessary to alleviate anomalous burning conditions.

X1.11.2 For building products, the use of the retainer frame is recommended for testing in the horizontal orientation. For other product classes, the usage shall be in accordance with the governing application standard.

X1.12 The temperature measured by the thermocouple shown in Fig. 2 is not intended to represent a precise measurement of the effective radiation temperature, since the temperature reading is used only to maintain the heat flux on the test specimen at its pre-calibrated value.

X2. INTERLABORATORY TRIALS

X2.1 Scope of Studies

X2.1.1 For the ASTM interlaboratory trials, six laboratories tested the following materials: 6 mm fire retardant treated ABS ($\rho = 325 \text{ kg/m}^3$); 12 mm particleboard ($\rho = 640 \text{ kg/m}^3$); 6 mm black PMMA ($\rho = 1180 \text{ kg/m}^3$); 6 mm polyethylene ($\rho = 800 \text{ kg/m}^3$); 6 mm PVC ($\rho = 1340 \text{ kg/m}^3$); and 25 mm rigid polyisocyanurate foam ($\rho = 280 \text{ kg/m}^3$). For most of these materials, three replicates each were tested in two orientations (horizontal and vertical) and at two irradiance levels (25 and 50 kW/m^2).

X2.1.2 Data from the ASTM trials were supplemented by data developed during an analogous set of trials conducted by ISO, using functionally the same protocol. The materials tested in the ISO trials were: 25 mm black PMMA ($\rho = 1180 \text{ kg/m}^3$) [same material as tested by ASTM, but in a different thickness]; 30 mm rigid polyurethane foam ($\rho = 33 \text{ kg/m}^3$); 12 mm particleboard ($\rho = 640 \text{ kg/m}^3$) [same material as tested by ASTM]; 3 mm hardboard ($\rho = 1010 \text{ kg/m}^3$); 10 mm gypsum board ($\rho = 1110 \text{ kg/m}^3$); and 10 mm fire retardant treated particleboard ($\rho = 750 \text{ kg/m}^3$). For most of these materials, three replicates each were tested in two orientations (horizontal and vertical) and at two irradiance levels (25 and 50 kW/m^2) by six to eight laboratories.

X2.2 Method of Analysis

X2.2.1 Basic guidance was received from Practices E 177 and E 691. However, these practices refer to various possibilities of reporting repeatability and reproducibility at 1.0, 2.0, 2.83, or 3.0 times the pertinent standard deviations. The standard deviation may be computed with respect to the average value or with respect to two sets of results. Furthermore, they leave the treatment of outliers largely to the discretion of the analyst. This presents certain difficulties in comparing results to other studies. It was, specifically, desired to treat the ASTM and ISO trials in a similar manner. The

solution was found in adopting the prescriptions contained in ISO 5725. The ISO standard, which can be viewed as a stricter subset of the ASTM instructions, prescribes a single fixed procedure. It mandates that repeatability and reproducibility be reported to 2.8 standard deviations, and also provides fixed instructions on how to handle the issue of outliers.

X2.2.2 The ASTM and ISO results were first analyzed separately in accordance with the equations given in ISO 5725. The results for both series were found to be expressible as a linear error model, defined by Eq II in Par. 15.2 of ISO 5725. Furthermore, in all the cases where valid data were available from both series, the relationships for r and R showed very similar behavior. This allowed best estimate relationships for r and R to be derived from the combined data set (in cases where valid data were obtained in both series). The equations given in 14.1.3 constitute these best estimate values.

X2.3 Example of Using r and R Relationships

X2.3.1 The meaning of the equations for r and R given in 14.1.3 is best illustrated by means of an example. Suppose a laboratory tests a single sample of a certain material and determines that the time to ignition (sustained flaming) is 100 s. If the same laboratory now conducts a second test on the same material, the value of r is evaluated as:

$$r = 4.1 + 0.125 \times 100 = 17 \text{ s}$$

Then $100 - r = 83$ and $100 + r = 117$; thus, the probability is 95% that the result of the second test will fall between 83 and 117 s.

Suppose now that the same material is tested by a different laboratory. The value of R is evaluated as:

$$R = 7.4 + 0.220 \times 100 = 29 \text{ s}$$

Then $100 - R = 71$ and $100 + R = 129$; thus, the probability is 95% that the results from the test at that laboratory will fall between 71 and 129 s.

X2.4 Comparison to Results for Other Fire Tests

X2.4.1 A number of interlaboratory trials have been conducted on various fire tests. For most of them, the data would be difficult to compare, since the methods of analysis were not the same in each case. Since the present trials were analyzed in accordance with the specific prescription mandated by ISO 5725, however, it is possible to find an example that is directly comparable. This is the ISO radiant ignition test, ISO 5657. This test is especially interesting to compare since it uses a conical heater somewhat similar to the one used on the present

test method. Since that test is only a test for ignitability, only one variable is examined, the t_{ig} . The results of the ISO 5657 trials, analyzed in the same manner, were:

$$r = 2.9 + 0.241 t_{ig} \quad (X2.1)$$

$$R = 2.2 + 0.458 t_{ig} \quad (X2.2)$$

Comparison with Eq 20 and Eq 21 shows that, over most of the range, both the repeatability and reproducibility for the present test method are substantially better (smaller) than for the ISO 5657 test.

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